

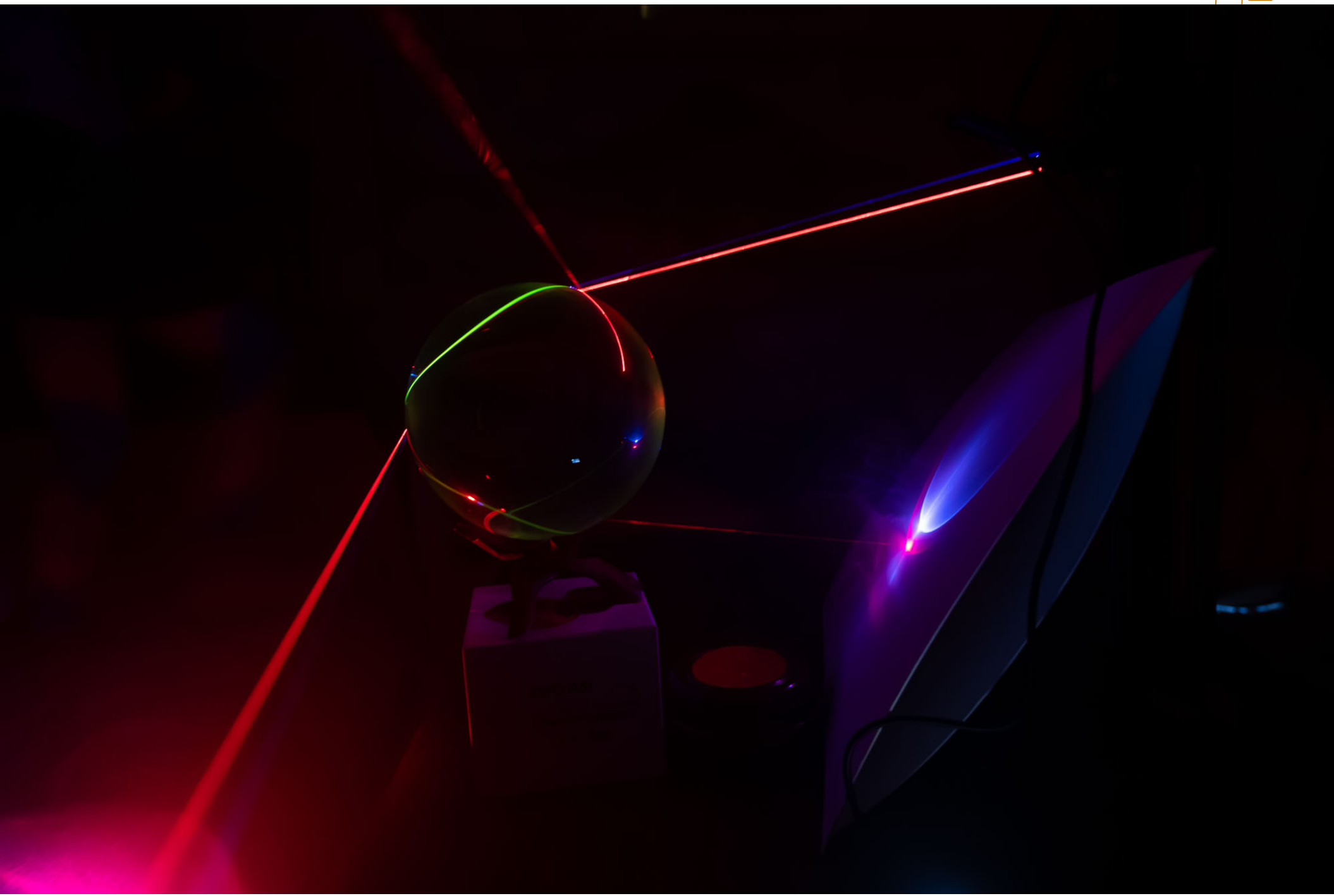
Focus, defocus and focal stacks

Frédo Durand

MIT EECS









Writeup about DSLR vs. mirrorless

- **https://www.diyphotography.net/the-dslr-will-probably-die-are-mirrorless-the-future-of-large-standalone-cameras/**

Paper on mobile photography

- **https://www.annualreviews.org/doi/pdf/10.1146/annurev-vision-093019-115521**

Annual Review of Vision Science

Mobile Computational Photography: A Tour

Mauricio Delbracio,[1] Damien Kelly,[1]
Michael S. Brown,[2] and Peyman Milanfar[1]

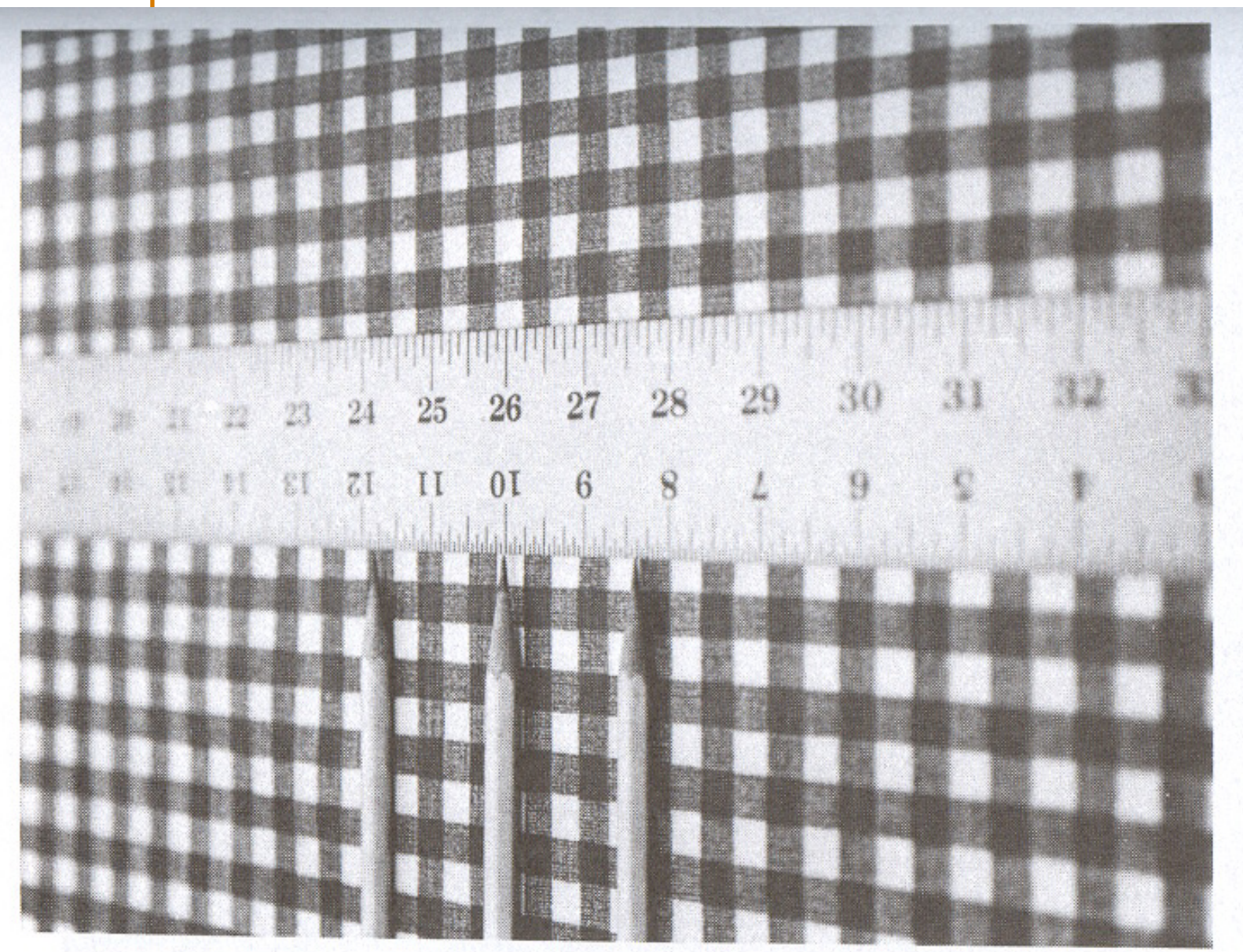
[1]Google Research, Mountain View, California 94043, USA; email: mdelbra@google.com, damienkelly@google.com, milanfar@google.com

[2]EECS Department, York University, Toronto, Ontario M6E 3N1, Canada; email: mbrown@eecs.yorku.ca

Don’t forget the survey on LLMs

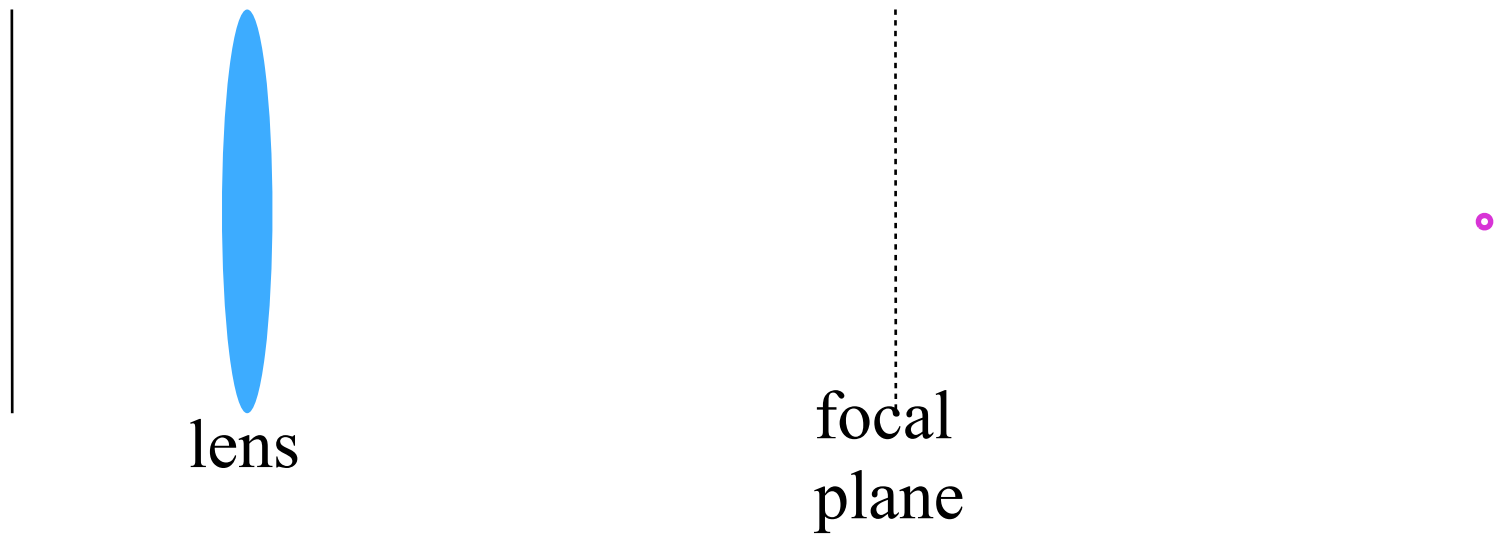
- **https://docs.google.com/forms/d/e/1FAIpQLScJDDd7k4ZVIvwejXMoLyQ3impDdKwDShqyhIpEcd20sWf-WQ/viewform**
-

Depth of field


22 23 24 25 26 27 28 29 30 31 32
13 12 11 10 9 8 7 6 5 4

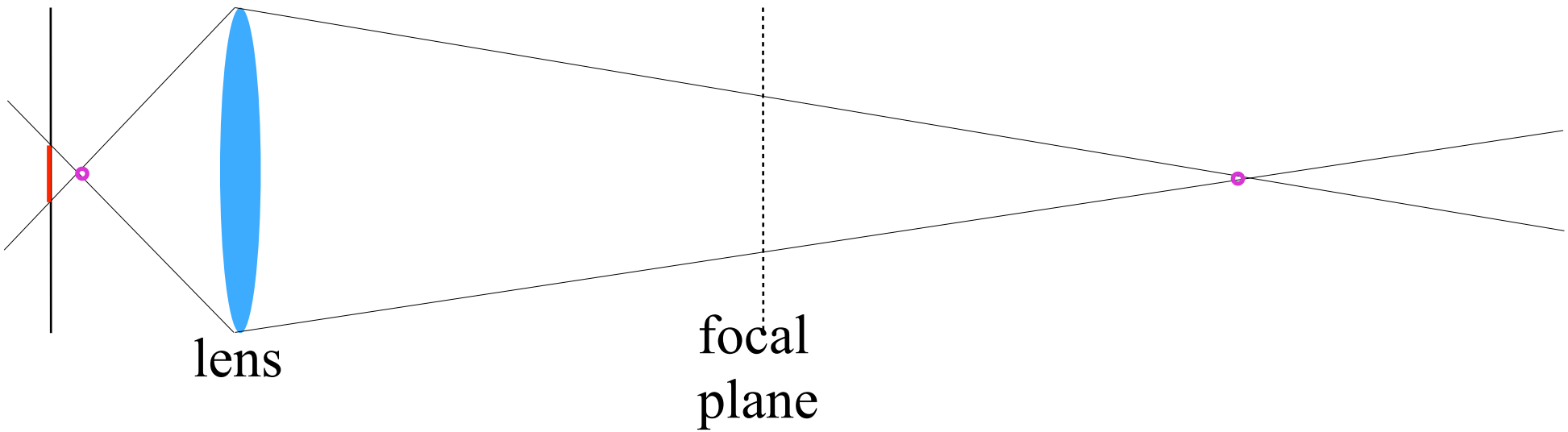
Misfocus

- **Points too far focus too close and project into a circle**
  - called circle of confusion



Misfocus

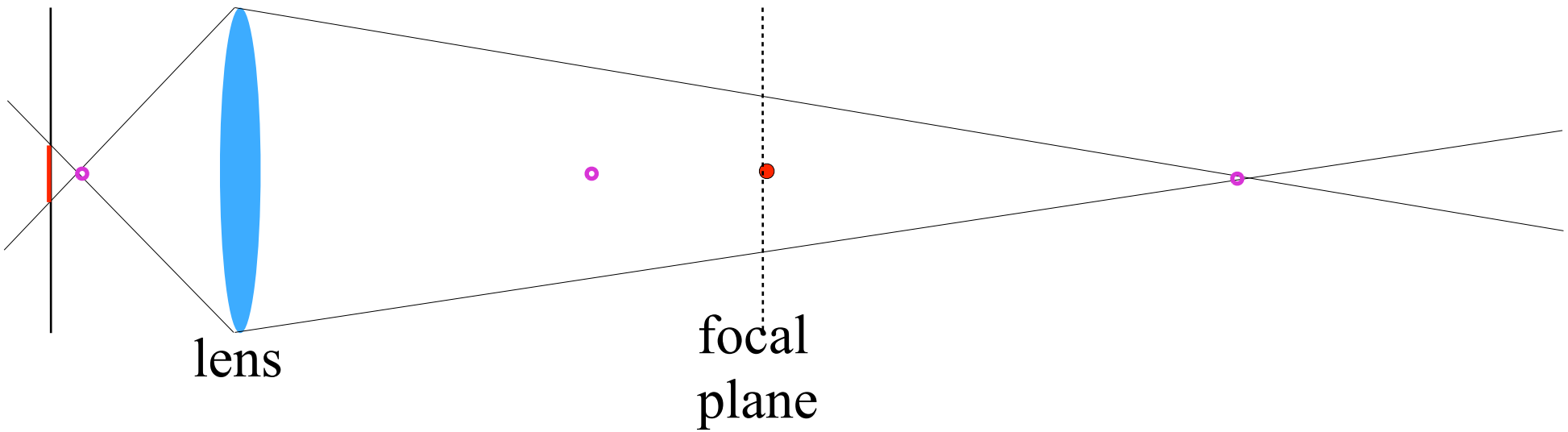
- **Points too far focus too close and project into a circle**
  - called circle of confusion



Depth of focus: more accurate view

- **Points too far focus too close and project into a circle**
- **Points too close focus too far and project into a circle**

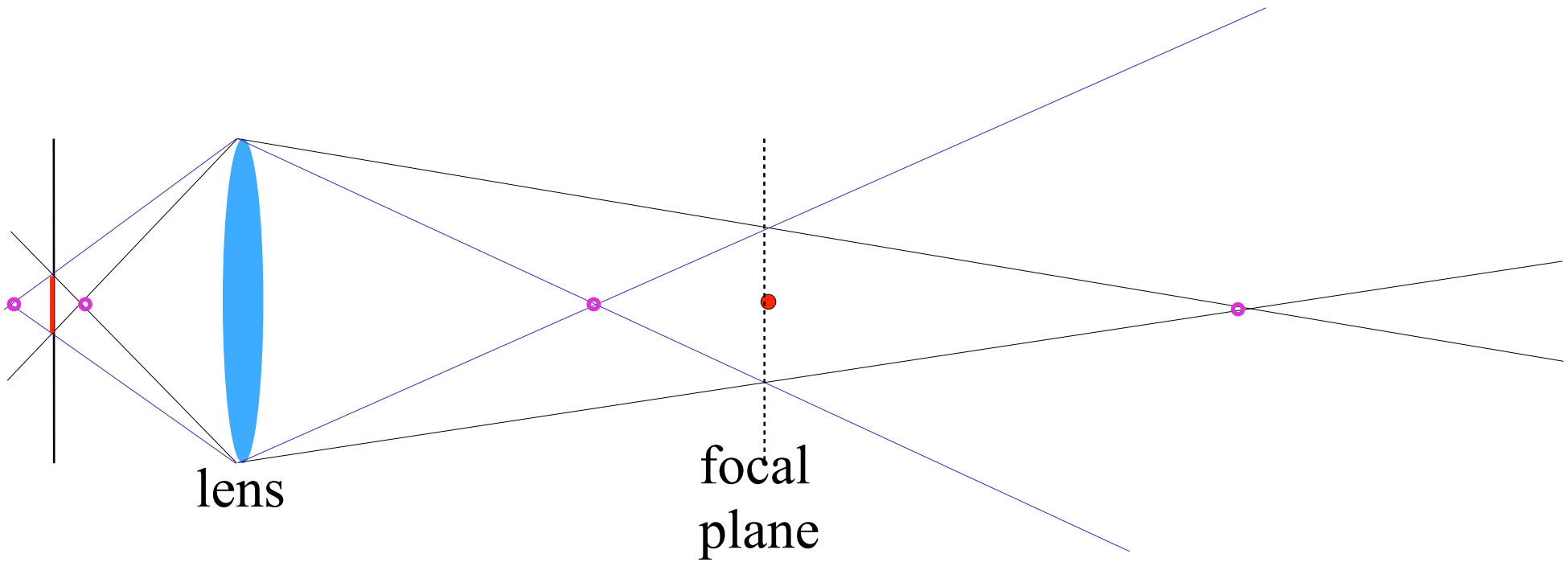
- **When the circle exceeds a given size, we declare the point out of focus**



Depth of focus: more accurate view

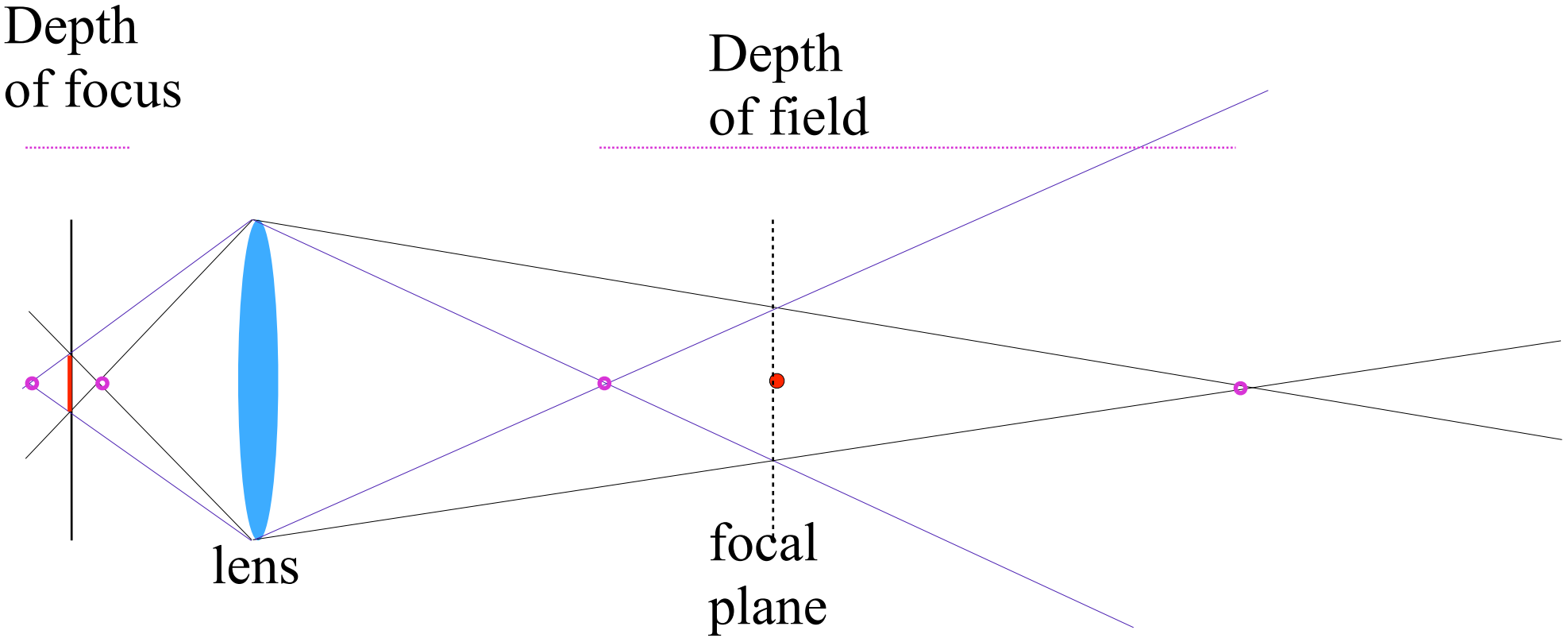
- Points too far focus too close and project into a circle
- Points too close focus too far and project into a circle

- When the circle exceeds a given size, we declare the point out of focus



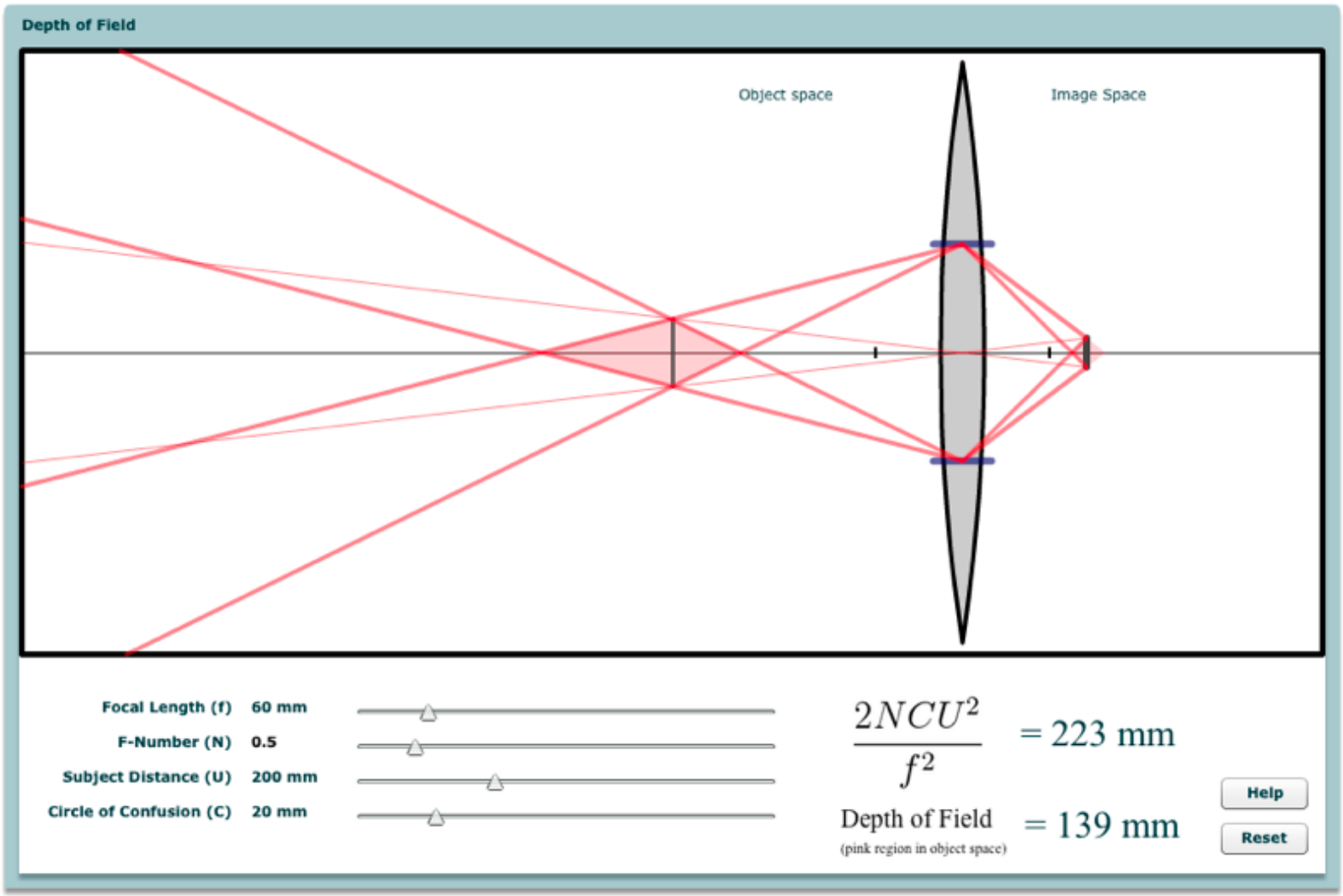
Depth of focus: more accurate view

- **Max circle of confusion can be achieved in two ways**
  - point that focuses too close, or too far
- **The distance between those points is the depth of focus**
  - Conjugate of depth of field



Applet demo

- **http://graphics.stanford.edu/courses/cs178/applets/dof.html**



Bottom line

- **Depth of field is increased by using a smaller aperture**
- **But lets in less light =>noise**
- **And also diffraction gets worse**
- **Can only be done up to a point**

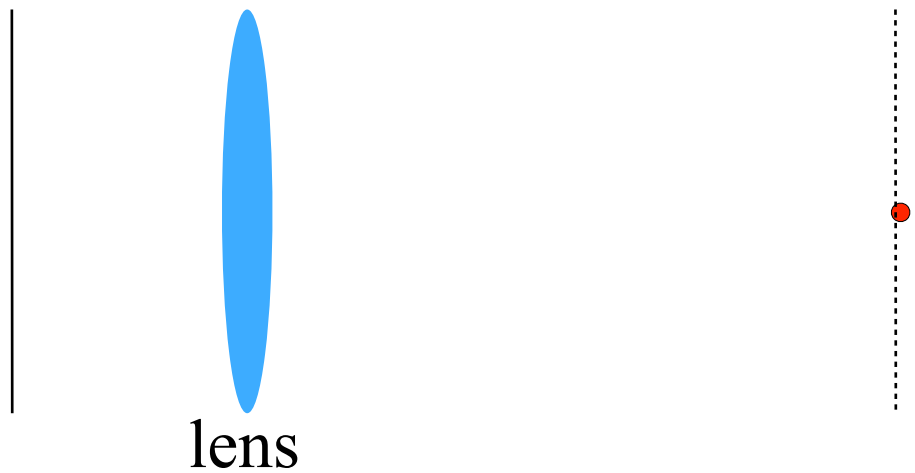
- **Especially challenging for macro photography**

- **Bottom light: even at smallest possible aperture, often not enough depth of field**

Depth of field calculation

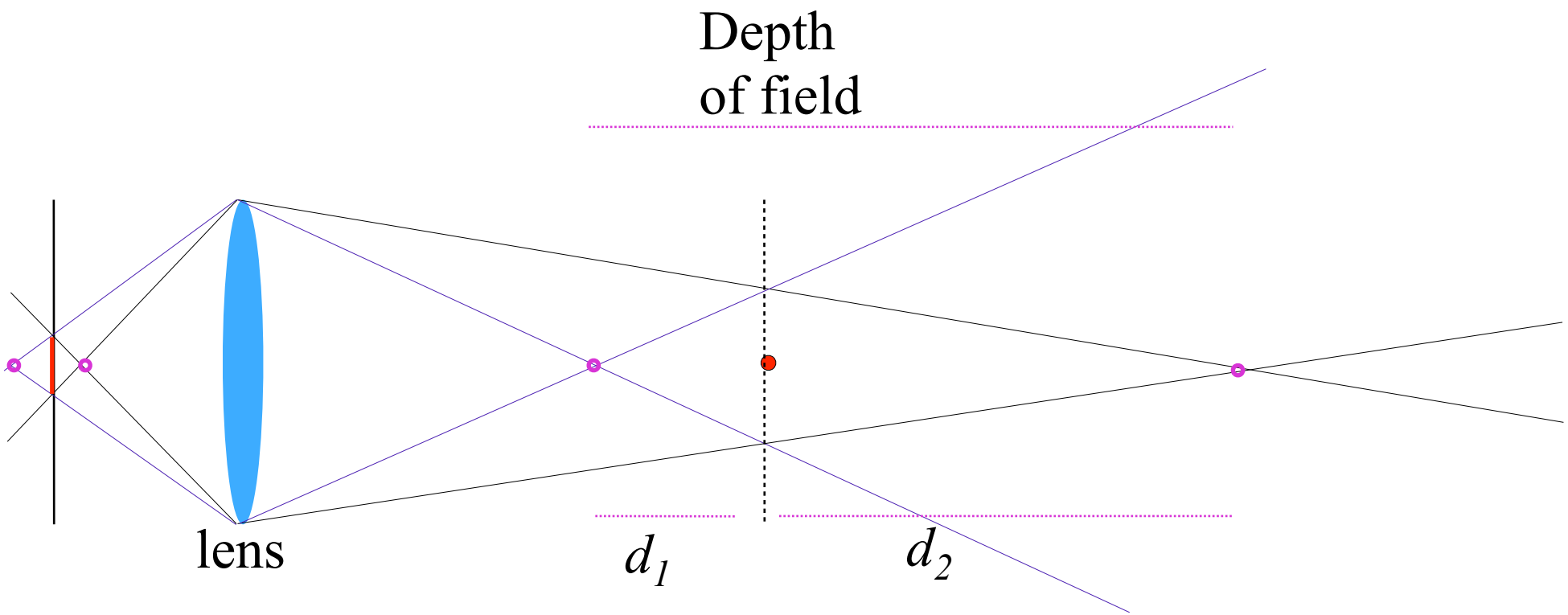
Depth of focus: more accurate view

- **Goal: compute depth of field**



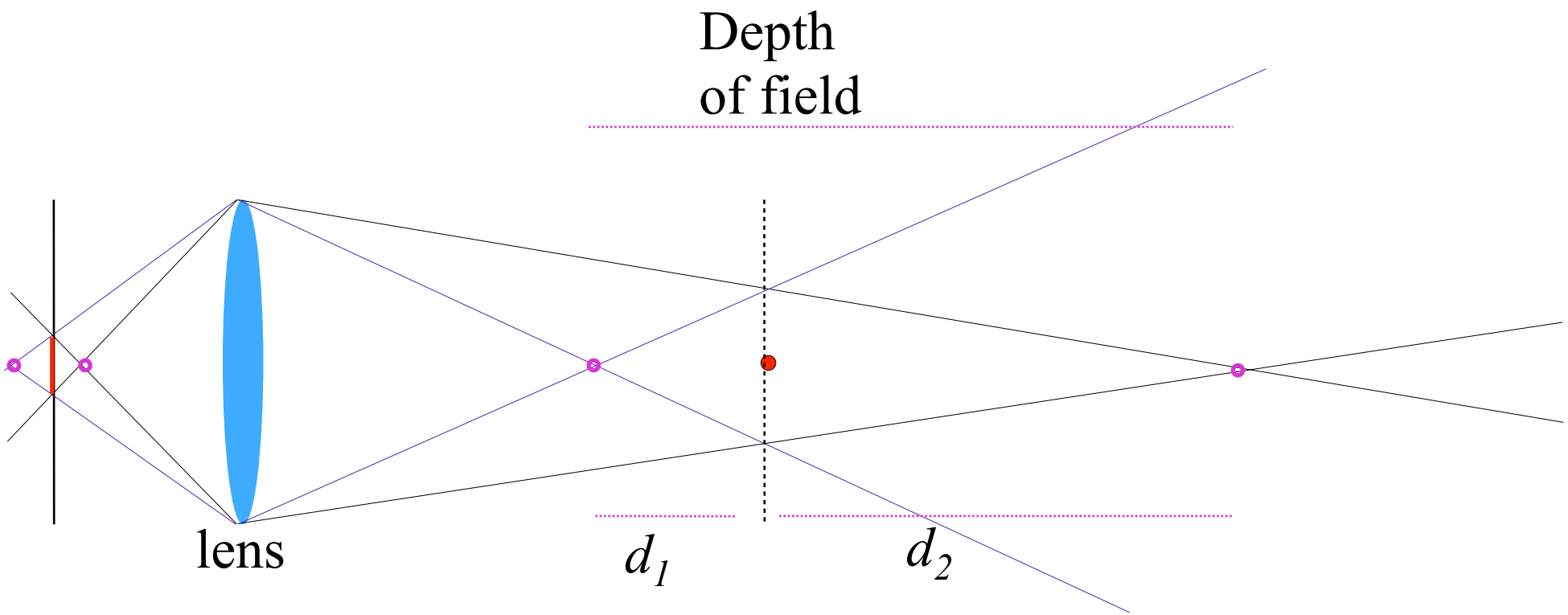
Depth of focus: more accurate view

- **Goal: compute depth of field**
  - distance d1 and d2 in front and behind the focal plane
  - given max circle of confusion



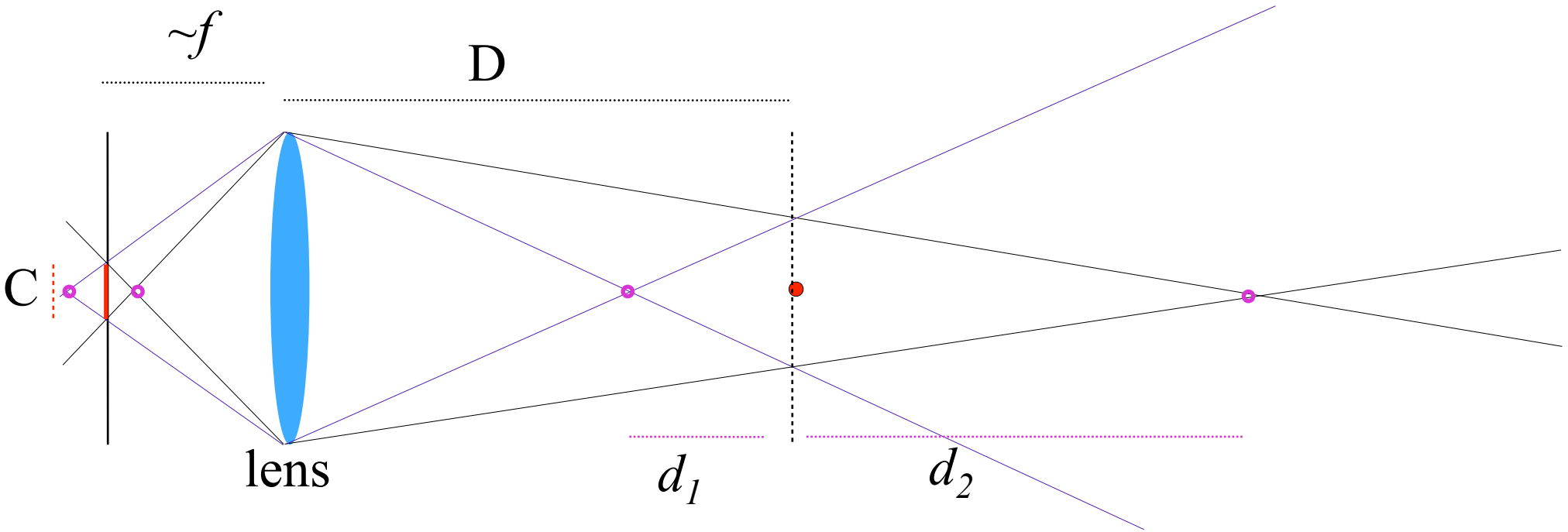
Depth of focus: more accurate view

- **Goal: compute depth of field**
  - distance d1 and d2 in front and behind the focal plane
  - given max circle of confusion
- **Solution: similar triangles**



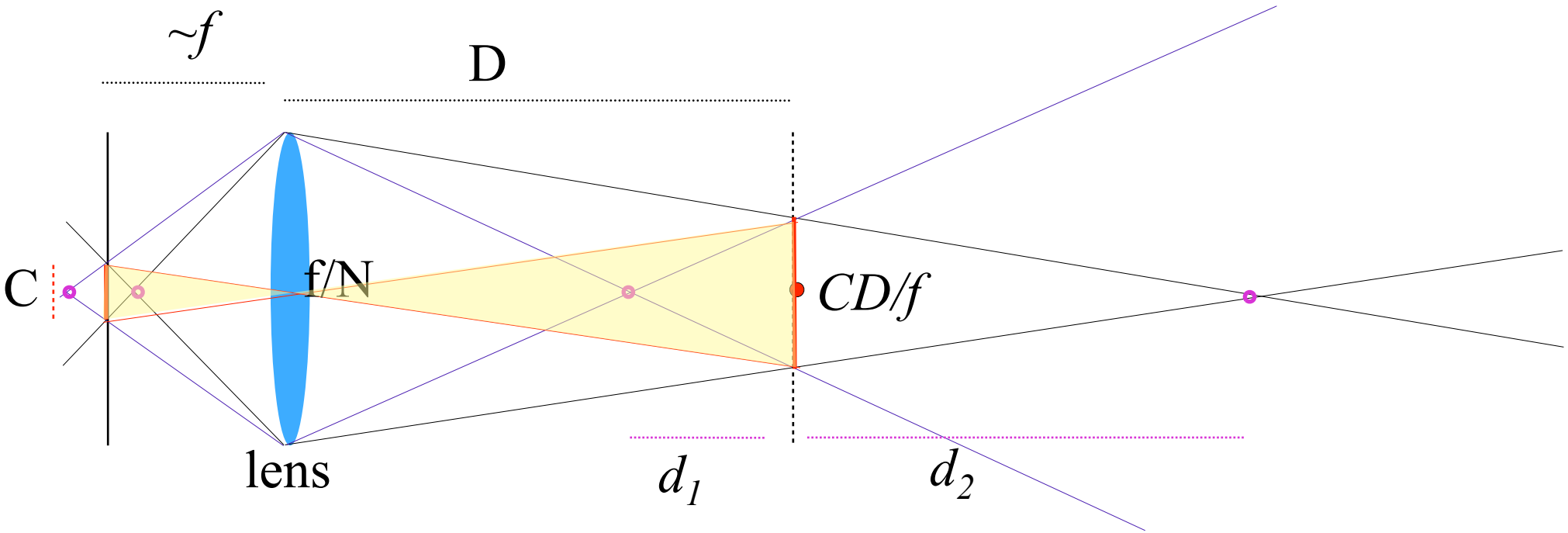
Depth of focus: more accurate view

- **Circle of confusion *C*,**
- **Focusing distance D, focal length *f*, aperture *N***



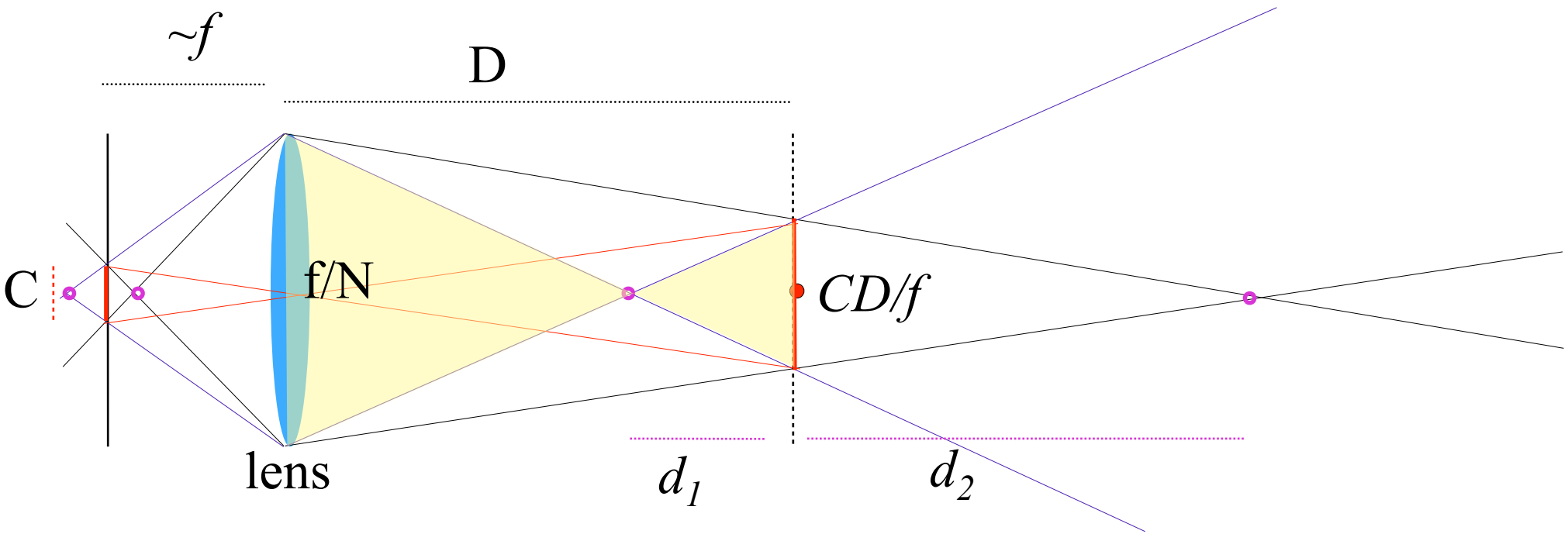
Depth of focus: more accurate view

- **Backproject the circle of confusion diameter C onto the focal plane**
  - Depends on *magnification factor ~ f/D*



Depth of focus: derivation

$$\frac{fd_1}{CD} = \frac{D - d_1}{f/N} \Rightarrow \frac{fd_1}{CD} + \frac{d_1}{f/N} = \frac{D}{f/N}$$



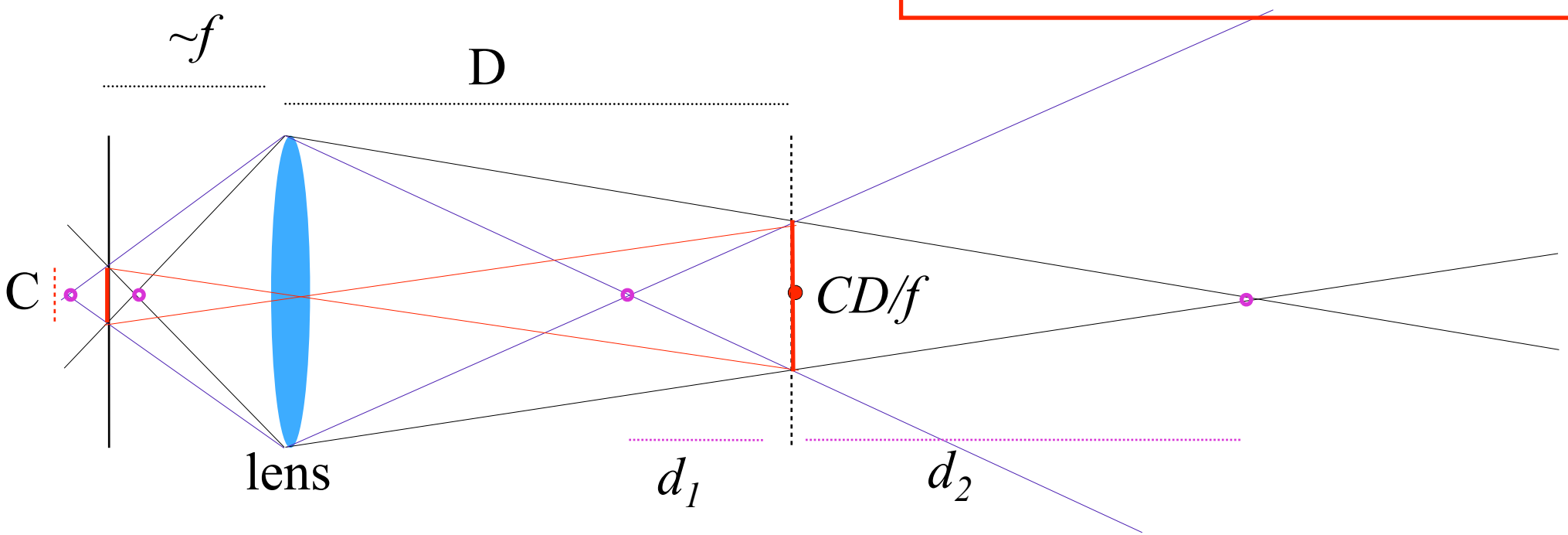
Depth of focus: more accurate view

$$\frac{fd_1}{CD} = \frac{D - d_1}{f/N}$$

$$\frac{fd_1}{CD} + \frac{d_1}{f/N} = \frac{D}{f/N}$$

$$d1\frac{f^2/N + CD}{CDf/N} = \frac{D}{f/N}$$

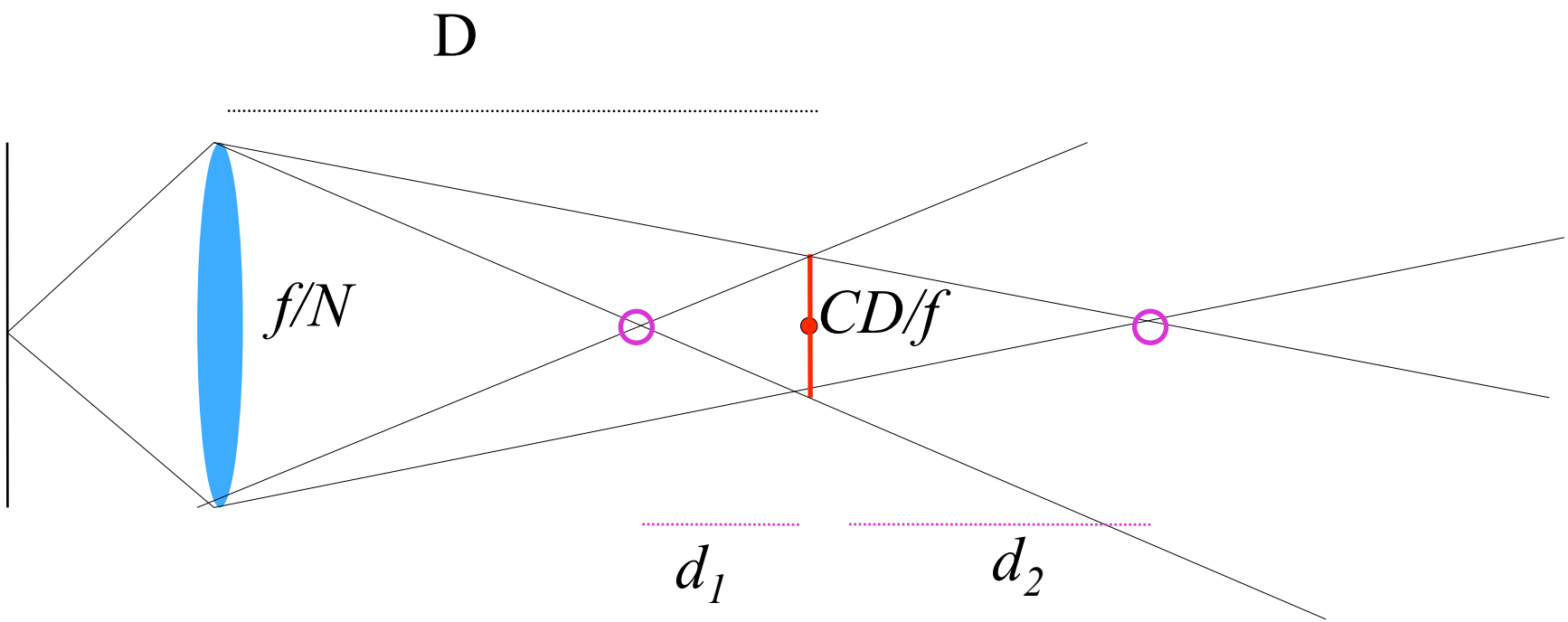
$$d1 = \frac{CD^2}{f^2/N + CD}$$



Deriving depth of field

$$d1 = \frac{NCD^2}{f^2 + NCD} \qquad d2 = \frac{NCD^2}{f^2 - NCD}$$

$$d = d_1 + d_2 = \frac{2NCD^2 f^2}{f^4 - N^2C^2D^2}$$

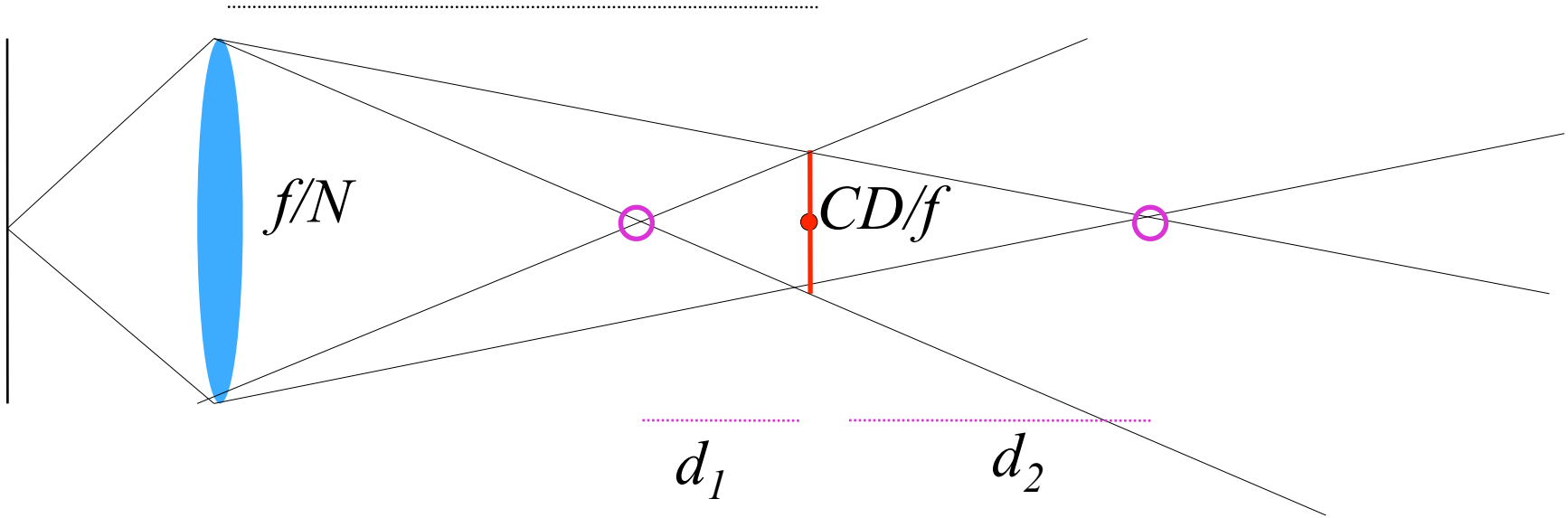


Deriving depth of field

$$d = \frac{2NCD^2 f^2}{f^4 - N^2C^2D^2}$$

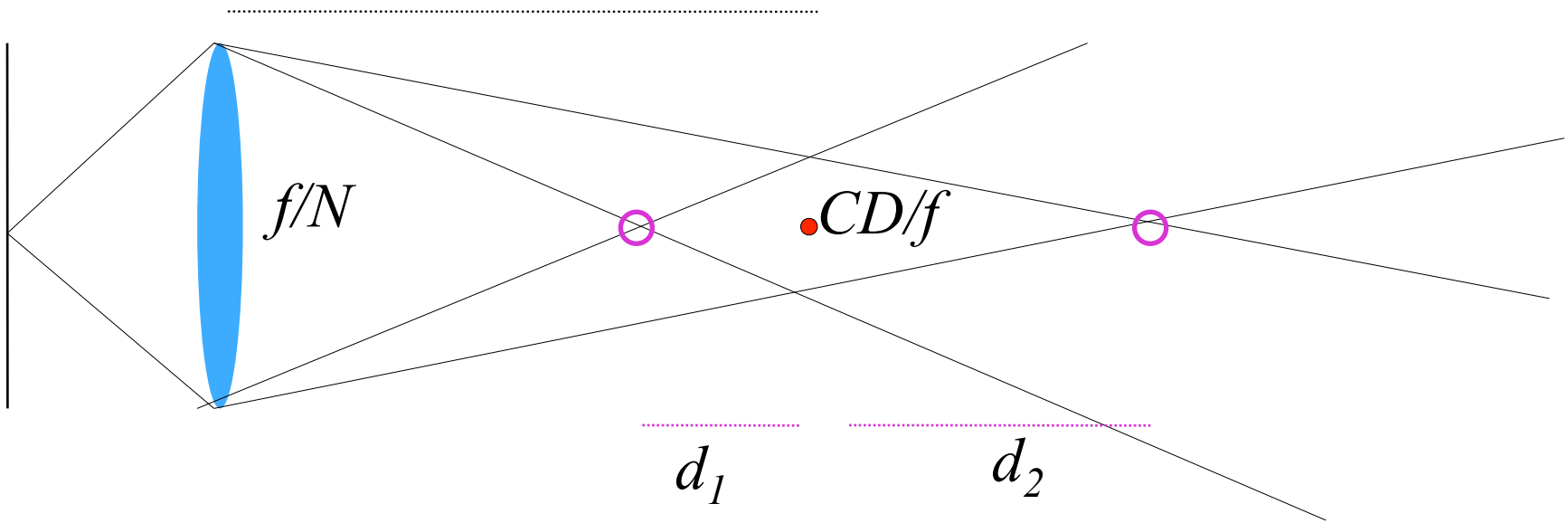
$N^2C^2D^2$ term can often be neglected when DoF is small
(conjugate of circle of confusion is smaller than lens aperture)

$$d = \frac{2NCD^2}{f^2}$$



Depth of field and aperture

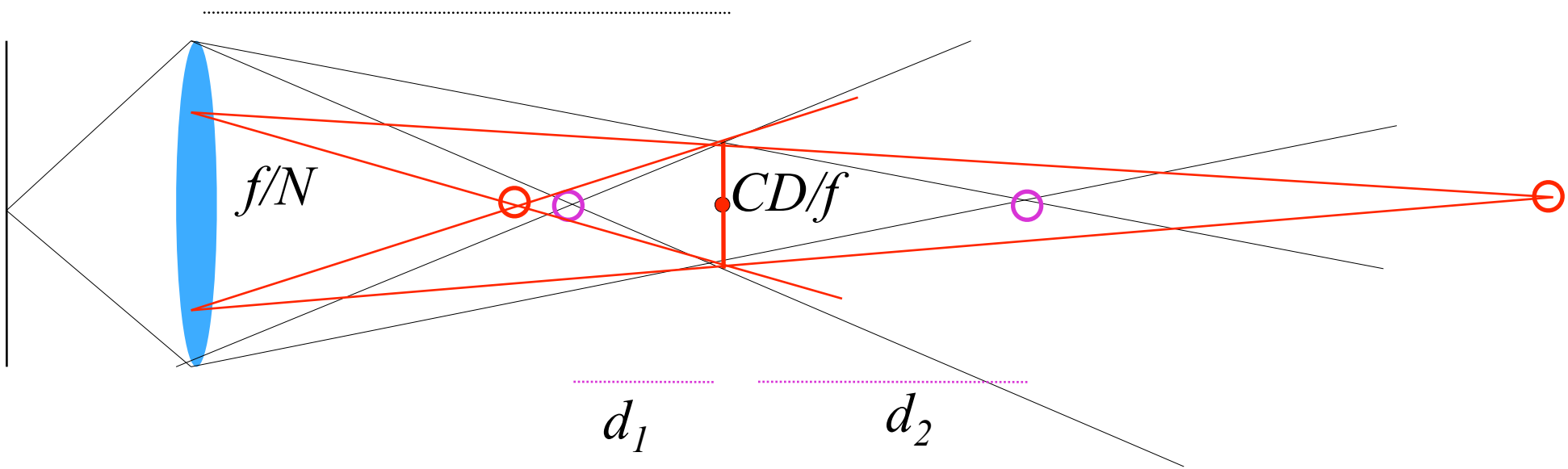
$$d = \frac{2NCD^2}{f^2}$$



Depth of field and aperture

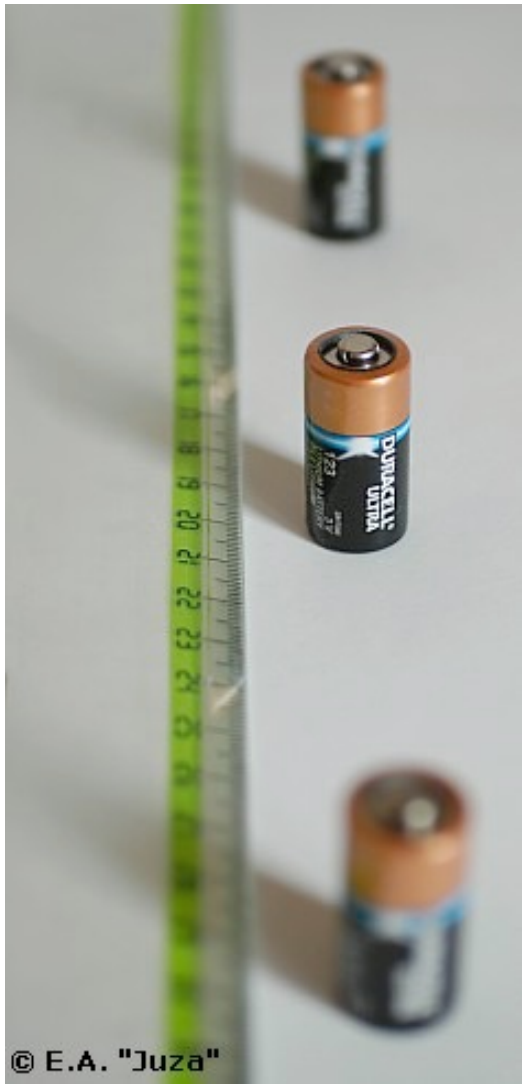
- **Linear: proportional to f number**
- **Recall: big f number N means small physical aperture**

$$d = \frac{2NCD^2}{f^2}$$

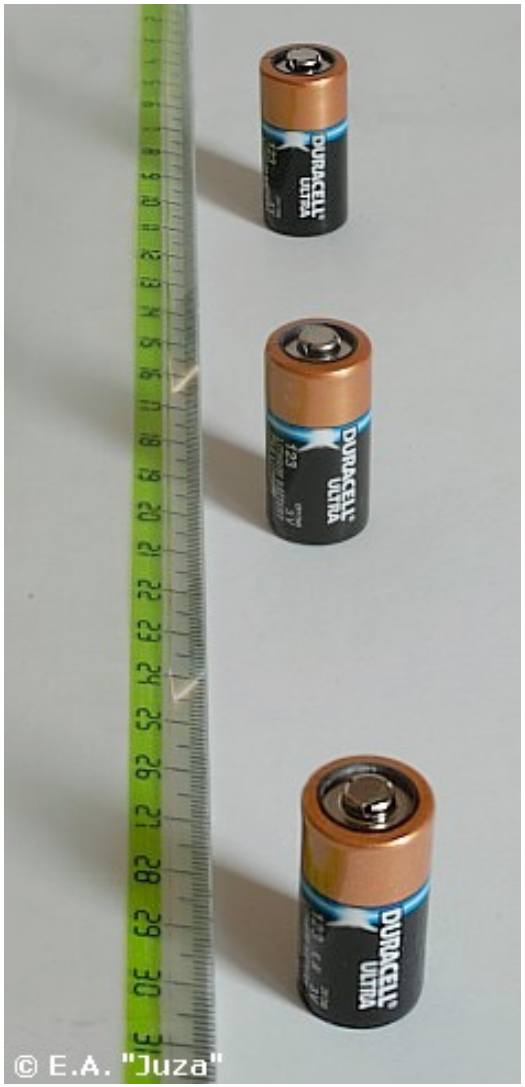


DoF & aperture

- **http://www.juzaphoto.com/eng/articles/depth_of_field.htm**



f/2.8



f/32

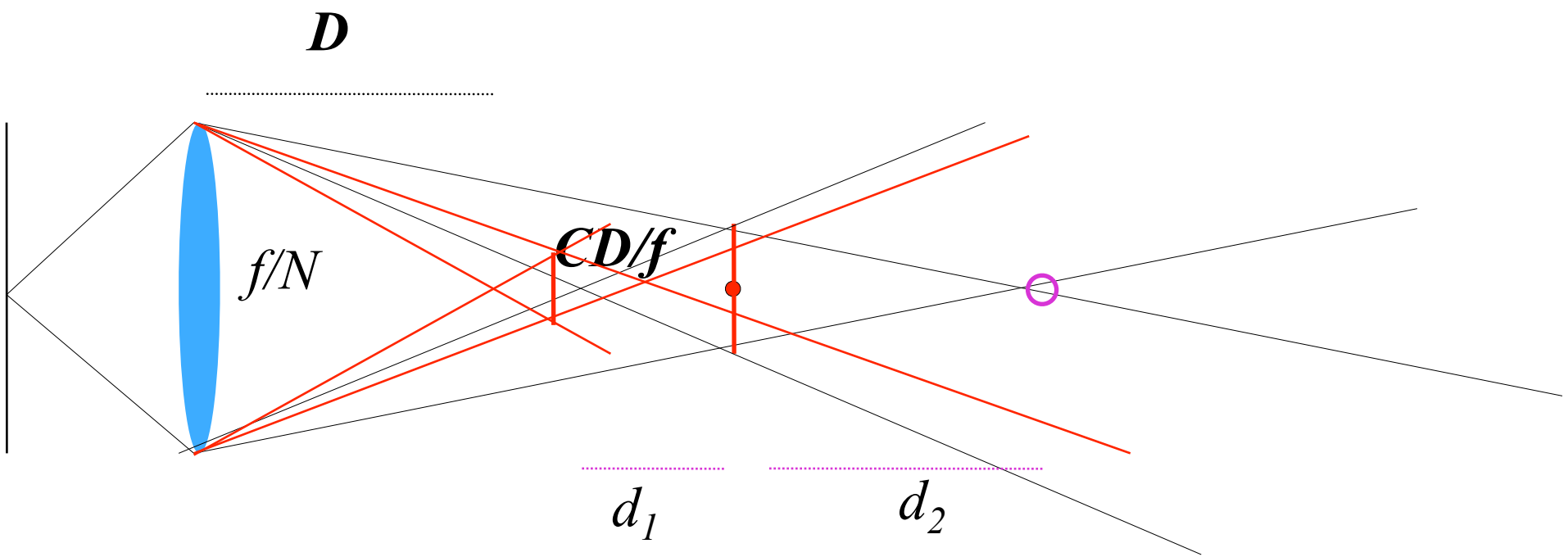
SLR viewfinder & aperture

- **By default, an SLR always shows you the biggest aperture**
- **Brighter image**
- **Shallow depth of field help judge focus**
- **Depth of field preview button:**
  - Stops down to the aperture you have chosen
  - Darker image
  - Larger depth of field

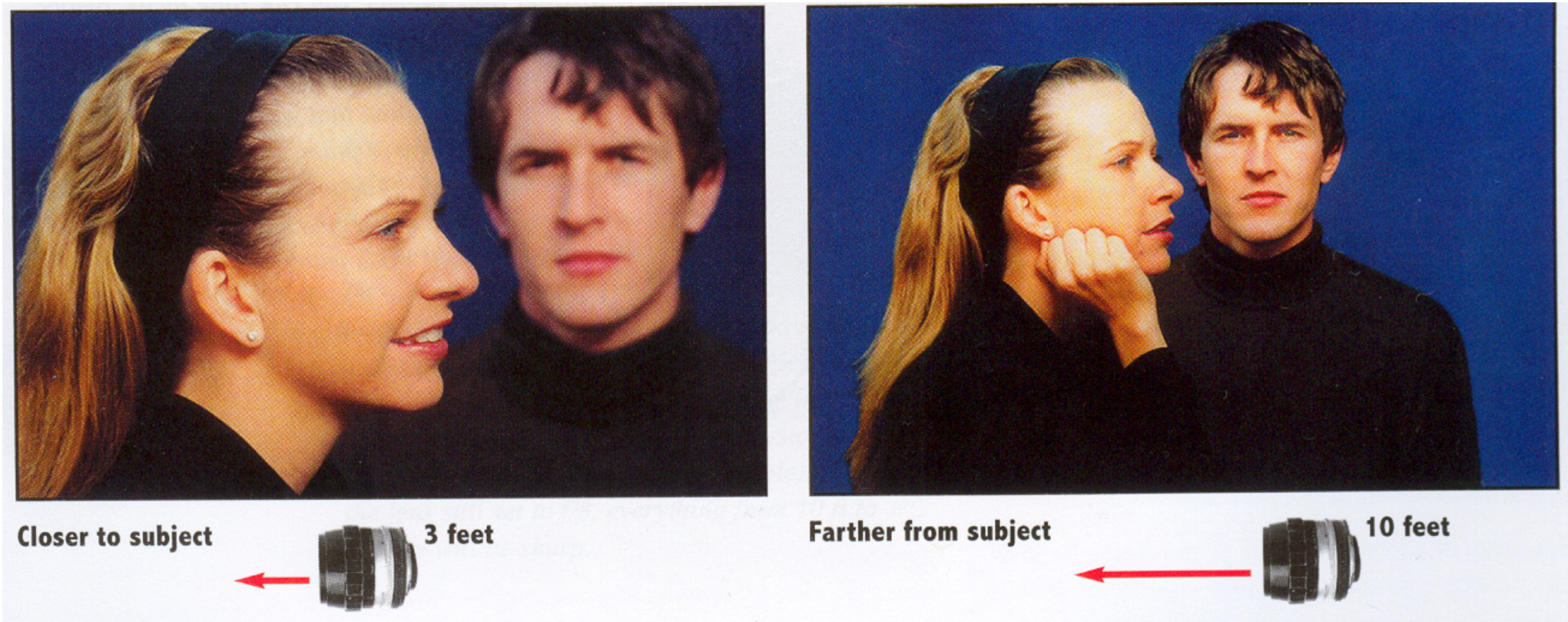
Depth of field and focusing distance

- **Quadratic (bad news for macro) (but careful, our simplifications are not accurate for macro)**

$$d = \frac{2NCD^2}{f^2}$$



Depth of field & focusing distance



From Photography, London et al.

Hyperfocal distance

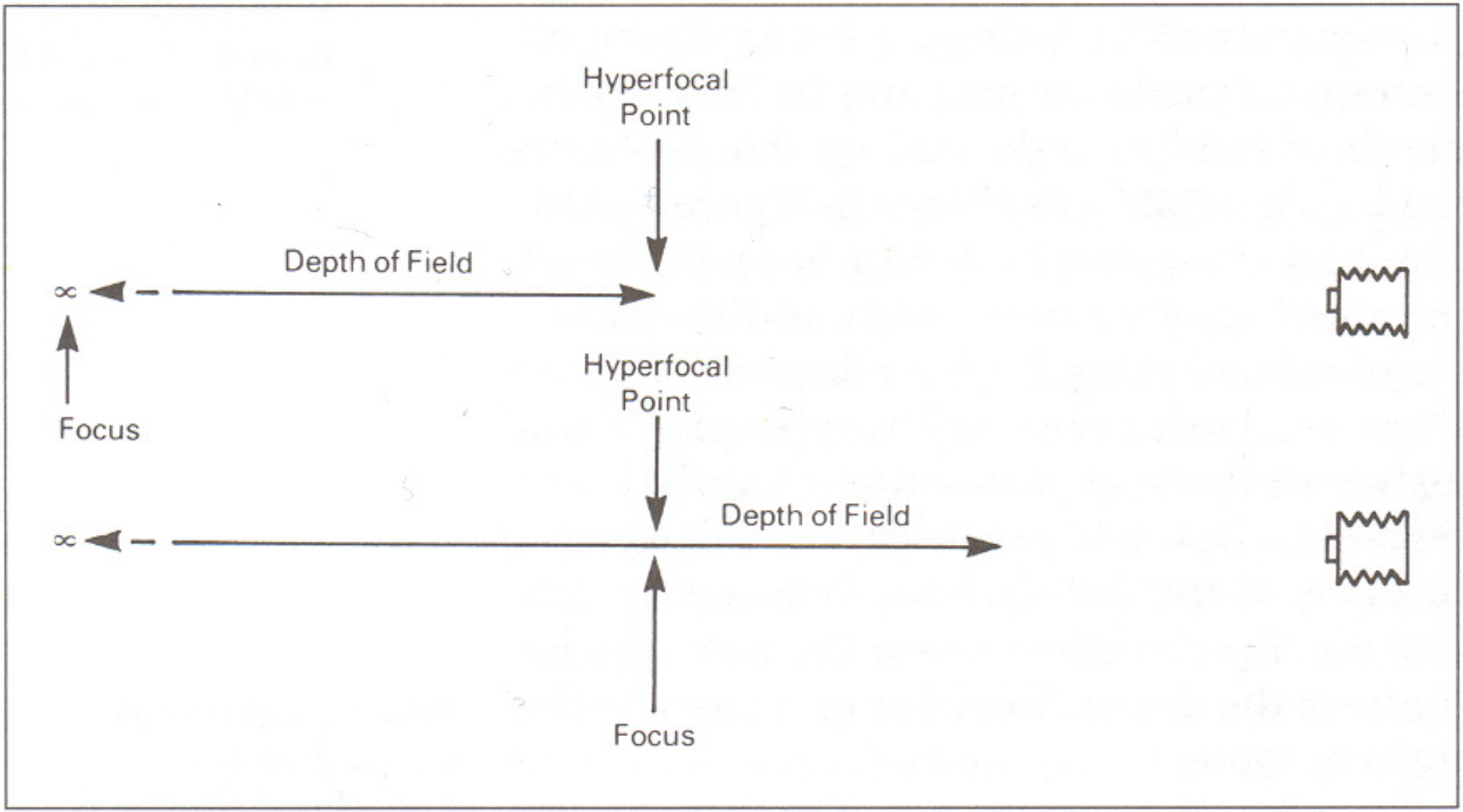


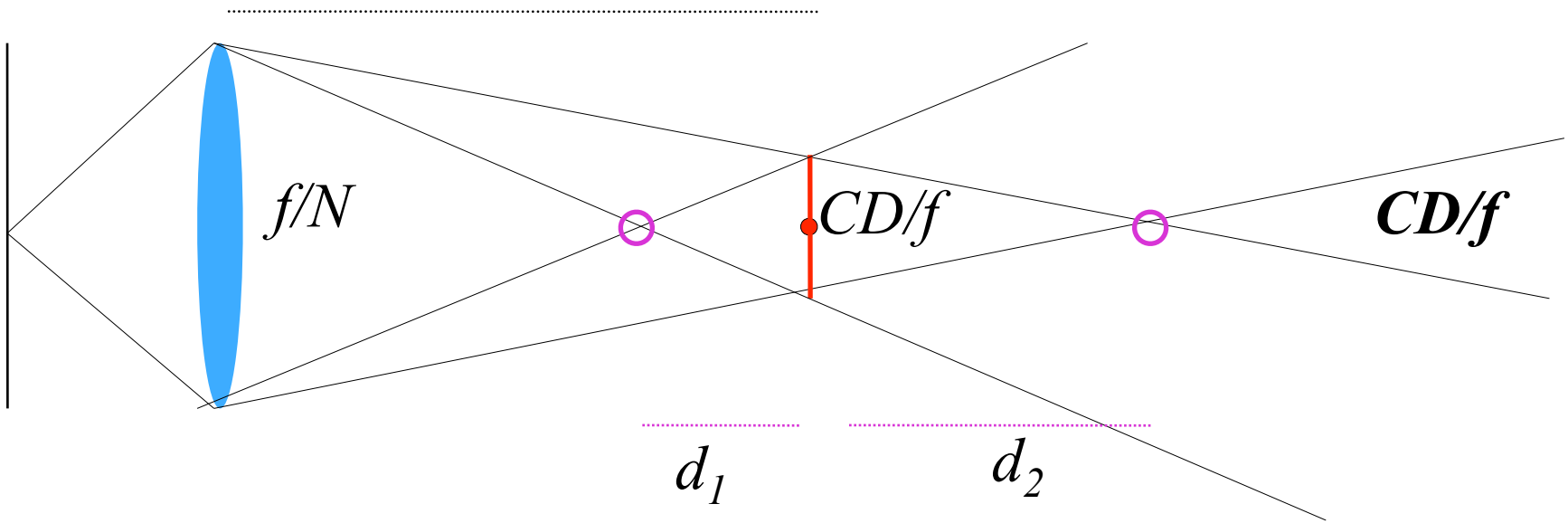
Figure 5–34 The hyperfocal distance is the closest distance that appears sharp when a lens is focused on infinity (top), or the closest distance that can be focused on and have an object at infinity appear sharp (bottom).

From Basic Photographic Materials and Processes, Stroebel et al.

Hyperfocal distance

- **Recall full formula**

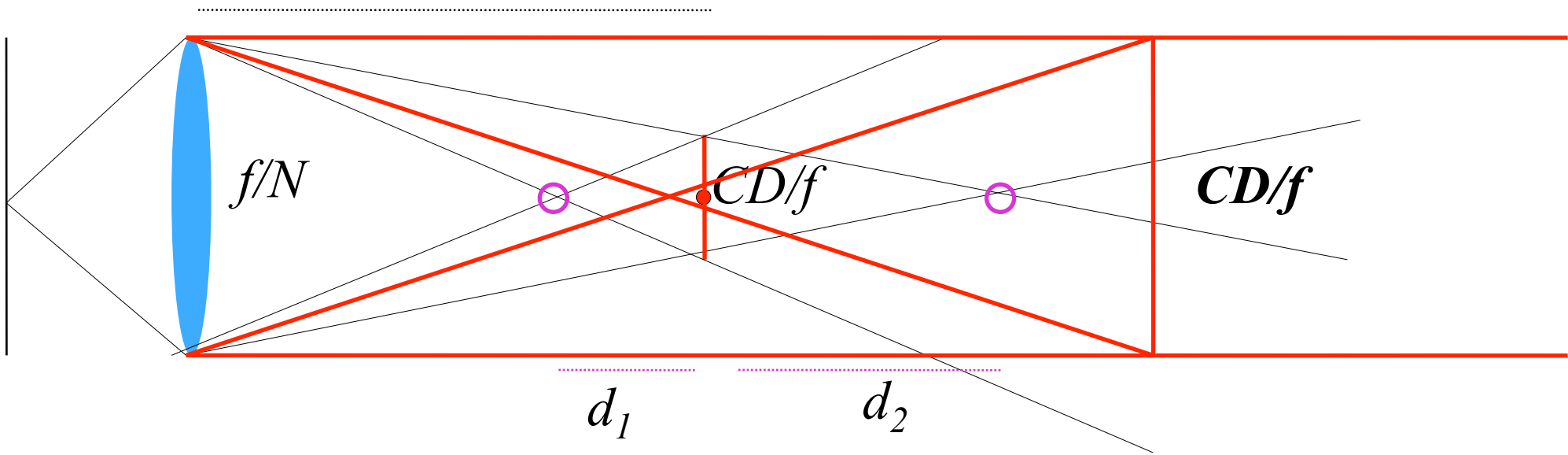
$$d = \frac{2NCD^2 f^2}{f^4 - N^2C^2D^2}$$



Hyperfocal distance

- When CD/f becomes bigger than f/N
- focus at $D=f^2/NC$ and sharp from D/2 till infinity
- Our other simplifications do not work anymore there: the denominator term has to be taken into account in

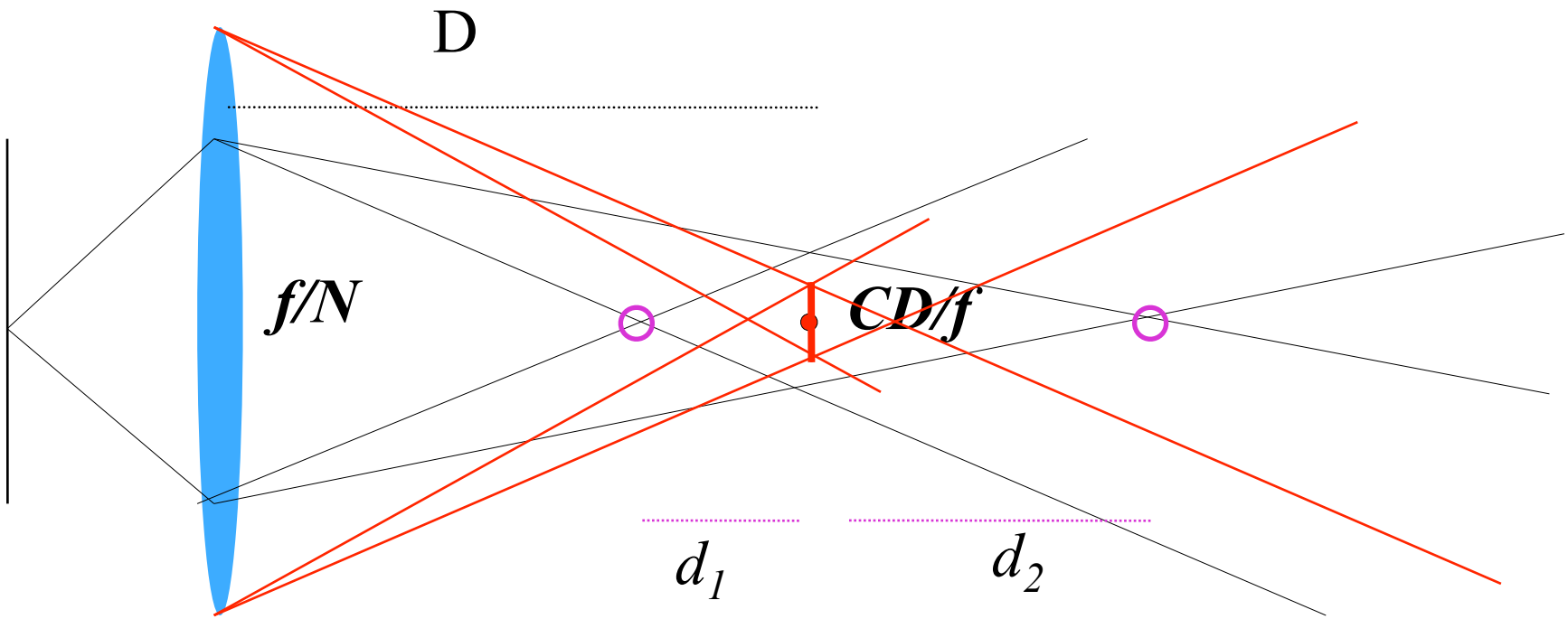
$$d = \frac{2NCD^2 f^2}{f^4 - N^2C^2D^2}$$



Depth of field and focal length

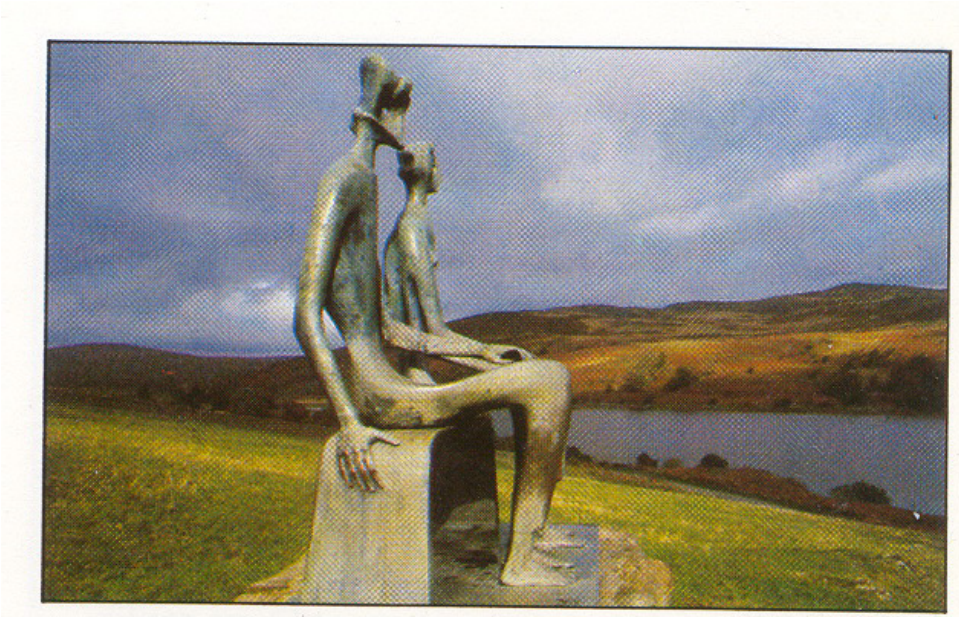
- **Inverse quadratic:**
  the lens gets bigger,
  the magnification is higher

$$d = \frac{2NCD^2}{f^2}$$

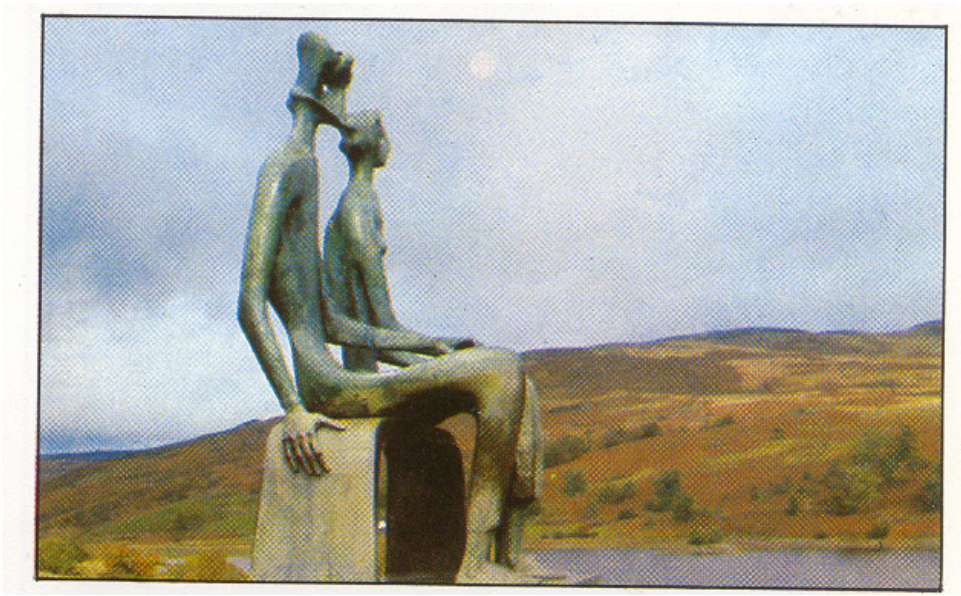


Depth of field & focal length

- **Recall that to get the same image size, we can double the focal length and the distance**
- **Recall what happens to physical aperture size when we double the focal length for the same f number?**
  - It is doubled



24mm

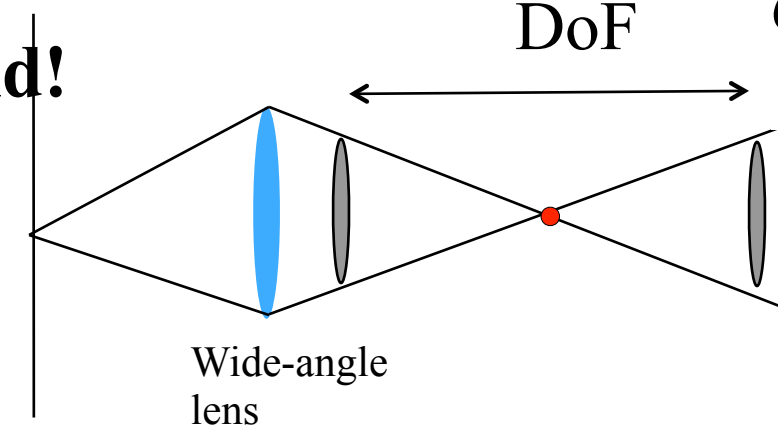


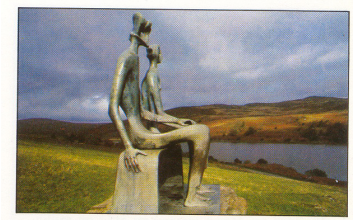
50mm

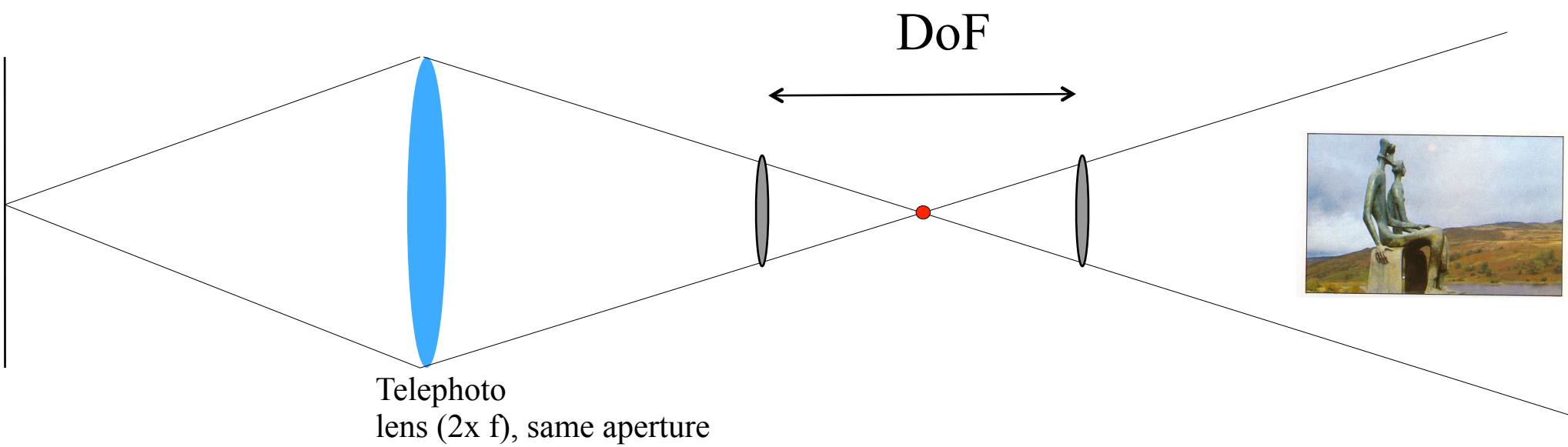
Depth of field & focal length

- **Same image size (same magnification), same f number**
- **Same depth of field!**

$$d = \frac{2NC'D^2}{f^2}$$







DoF & Focal length

- http://www.juzaphoto.com/eng/articles/depth_of_field.htm



50mm f/4.8



200mm f/4.8
(from 4 times farther)

See also http://luminous-landscape.com/tutorials/dof2.shtml

Important conclusion

- **For a given image size and a given f number, the depth of field (in object space) is the same.**
  - Might be counter intuitive.
  - Although only true if assumption respected (far from hyperlocal distance)

- **Very useful for macro where DoF is critical. You can change your working distance without affecting depth of field**

- **Now what happens to the background blur far far away?**

Important conclusion

- **For a given image size and a given f number, the depth of field (in object space) is the same.**
  - The depth of acceptable sharpness is the same
- **But background far far away looks more blurry**
  Because it gets magnified more
- **Plus, usually, you don't keep magnification constant**



To learn more

- **http://toothwalker.org/optics/dof.html**

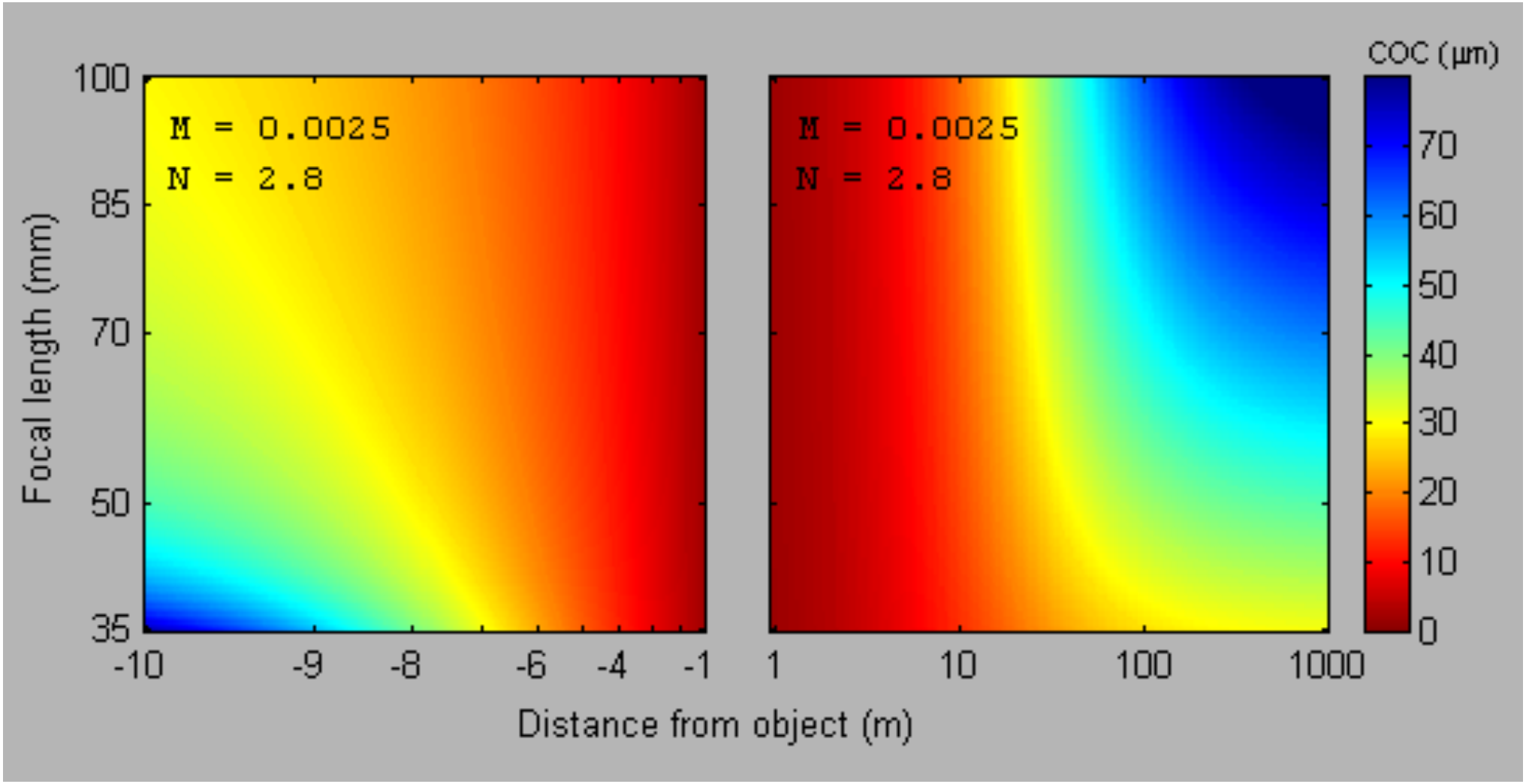


Figure 2. The circle of confusion versus distance at a fixed image magnification for a range of focal lengths.

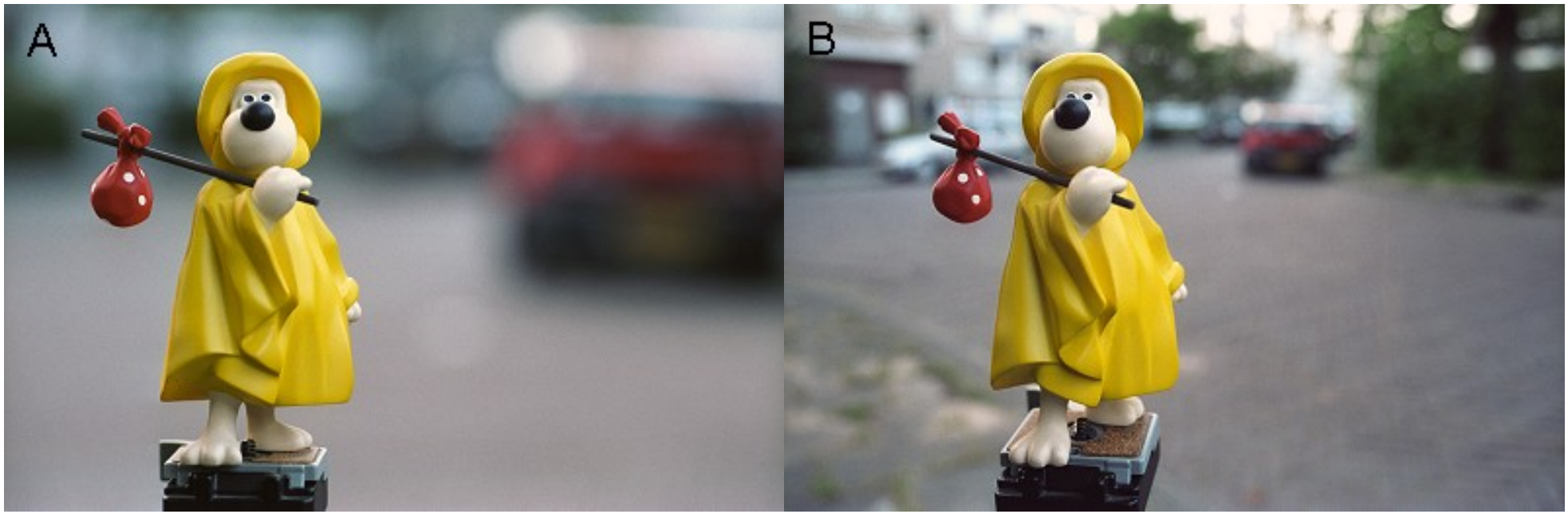
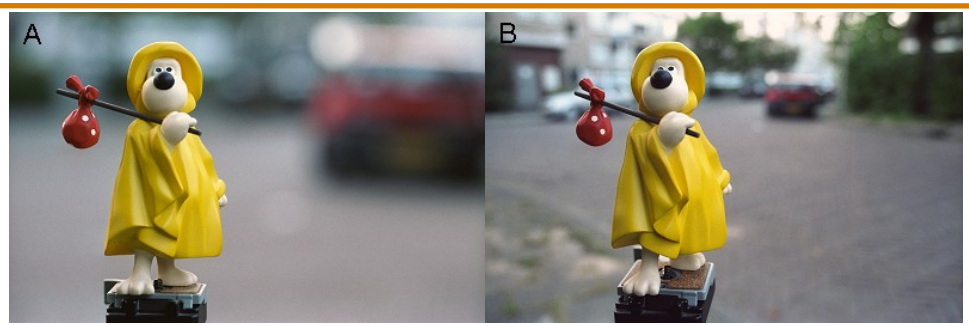


Figure 3. A: Gromit photographed with a 100-mm lens at f/4. B: Gromit photographed with a 28-mm lens at f/4. DOF is the same.

Same object space blur



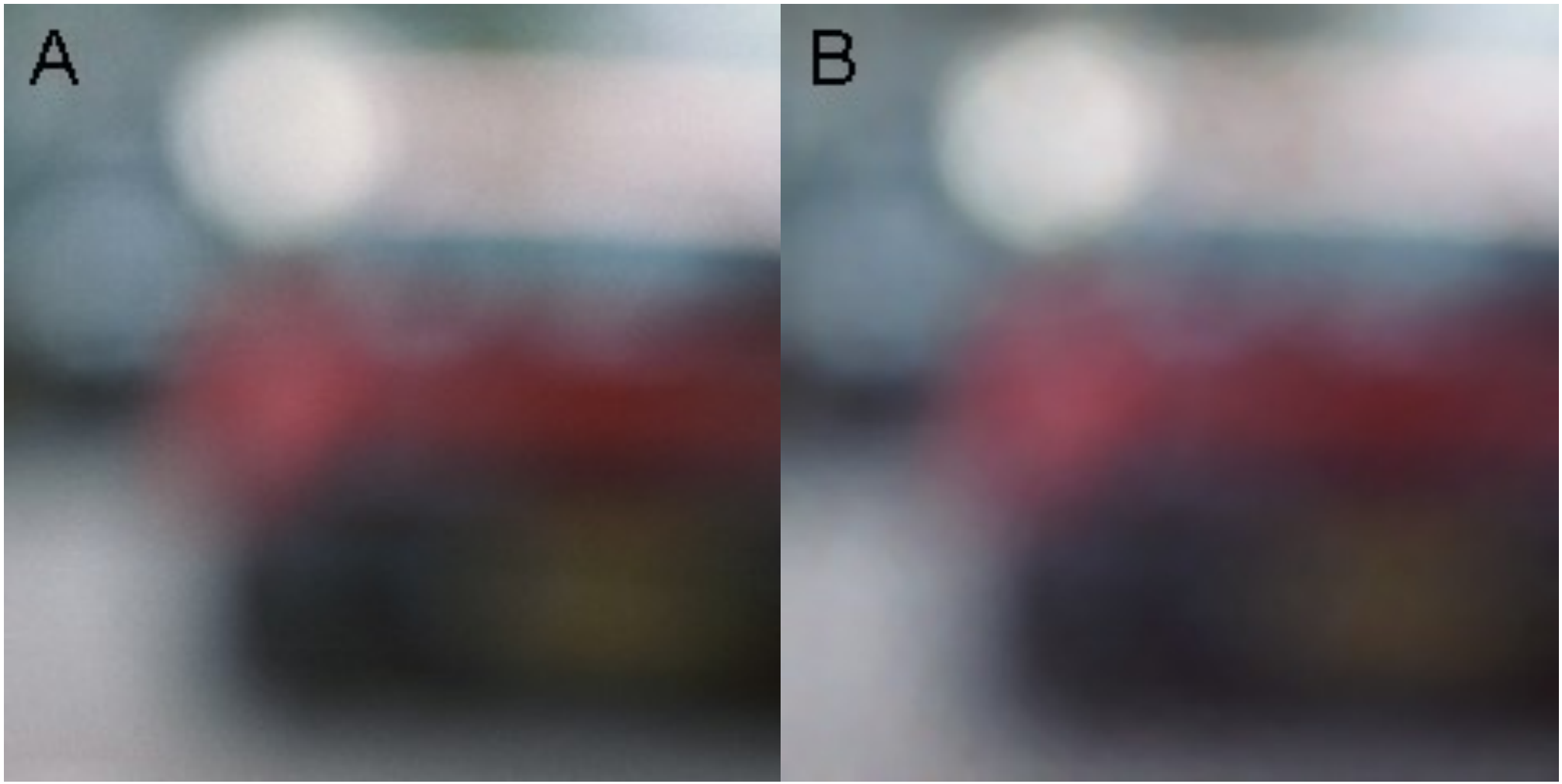


Figure 4. Background crop from the photographs in Fig. 3. A: 100-mm lens. B: 28-mm lens.

Good tutorials

- **http://petapixel.com/2011/05/10/a-detailed-explanation-of-depth-of-field-and-the-factors-that-affect-it/**
- **http://snodart.com/tutorials.php**
-

Recap

Effect of parameters

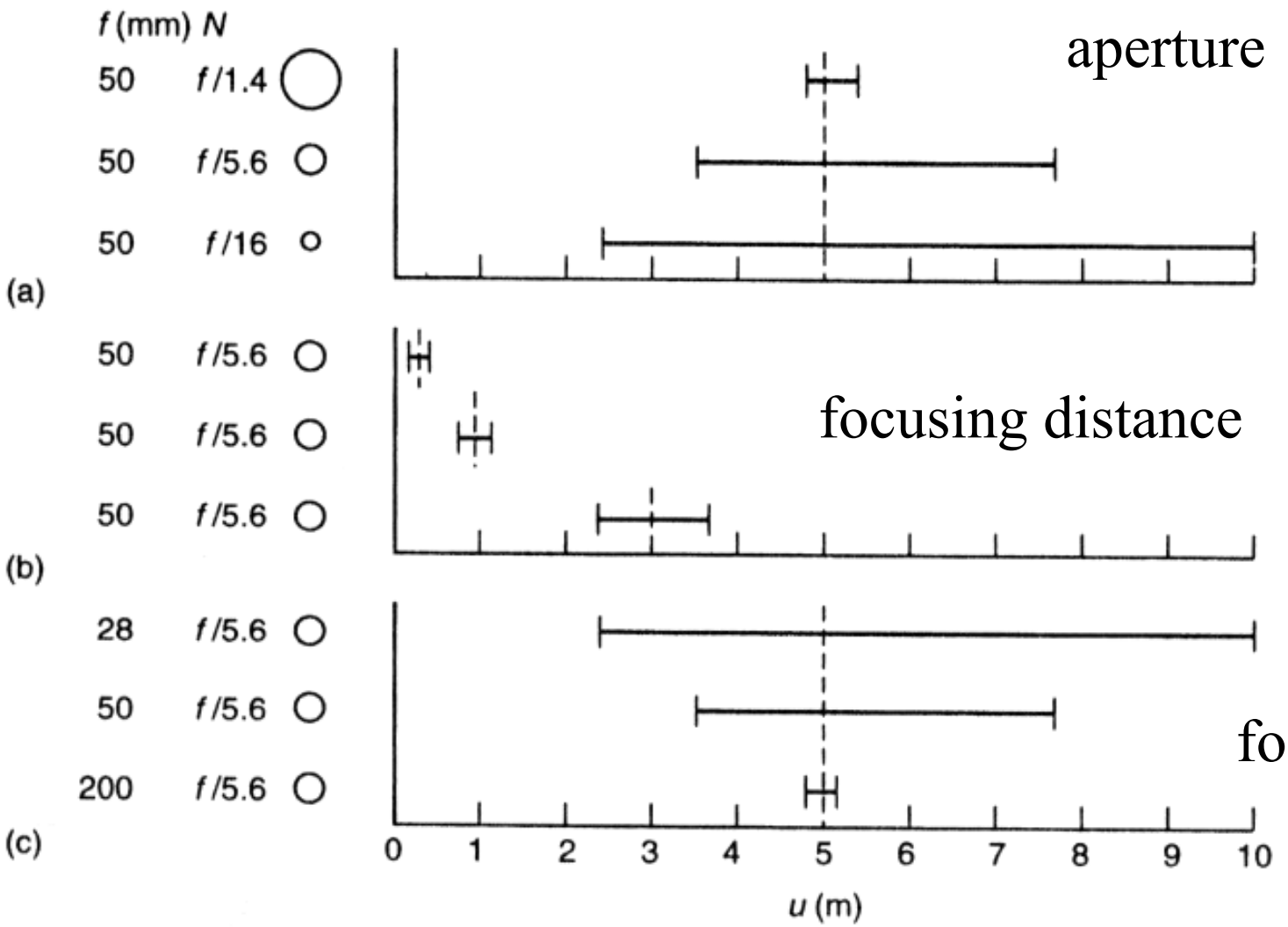
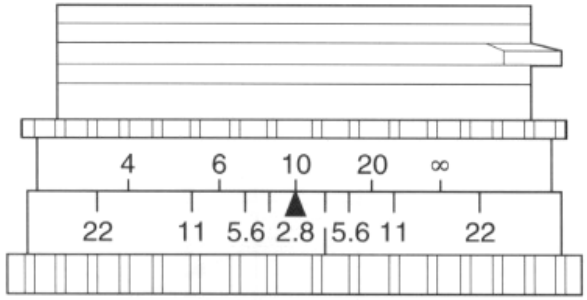


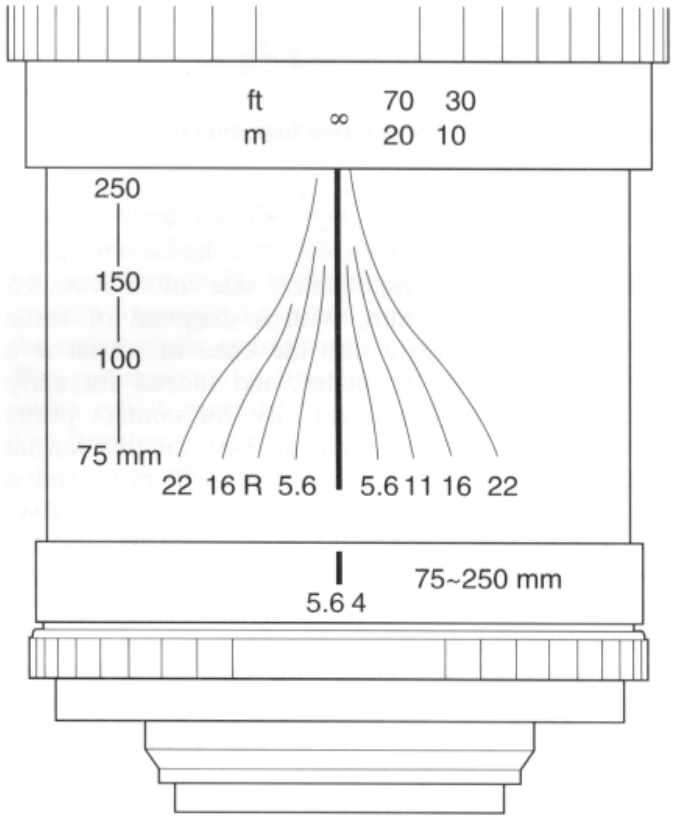
Figure 22.1 Depth of field Effect of the variables focal length (f), f-number (N) and focused distance (u) at constant value for circle of confusion (C). (a) Lens aperture varying from $f/1.4$ to $f/16$ with 50 mm lens focused on 5 m. (b) Focused distance varying from 0.5 to 3 m with 50 mm lens at $f/5.6$. (c) Focal length varying from 28 to 200 mm at $f/5.6$ focused on 5 m.

From applied photographic optics

DoF guides



(a)



(b)

Figure 4.20 Visual indication of depth of field. (a) Depth of field indicator scale. (b) Converging scales on a 75–250 mm *f*/4 zoom lens, including an infrared focus correction mark R

From "The Manual of Photography" Jacobson et al

Is depth of field good or evil?

- It depends, little grasshopper
- Want huge DoF: landscape, photojournalists, portrait with environment
- Shallow DoF: portrait, wildlife



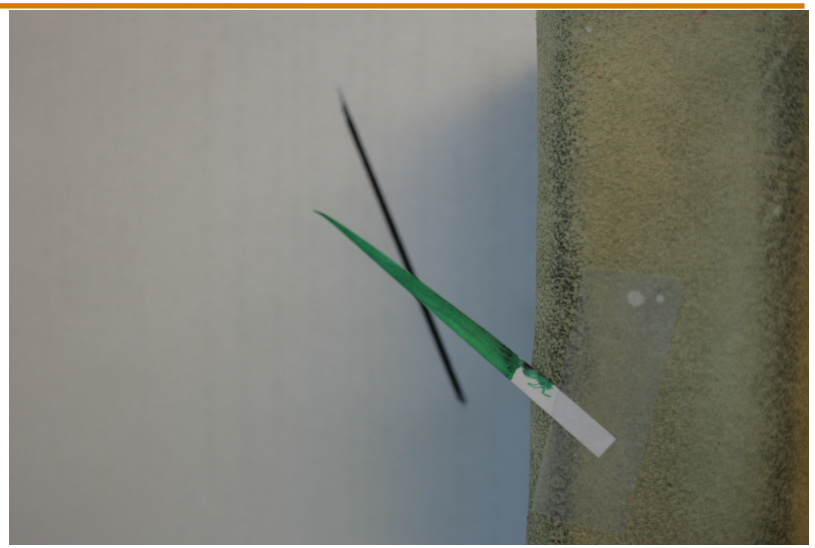
Michael Reichman



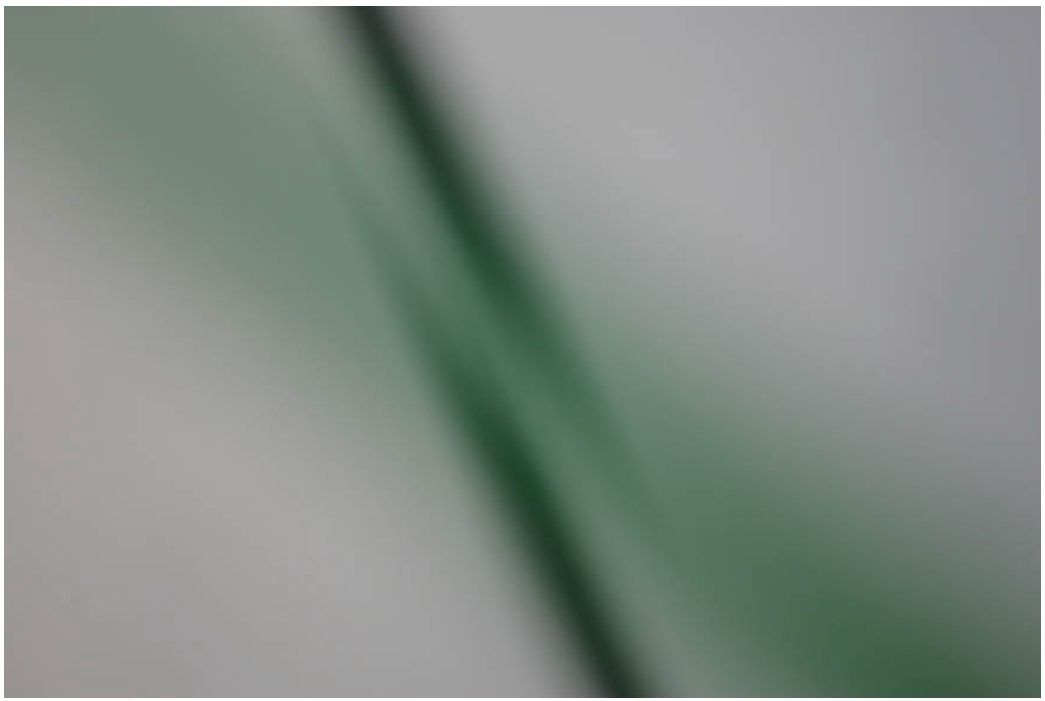
Steve McCurry

Crazy DoF images

- **By Matthias Zwicker**
- **The focus is between the two sticks**



Sharp version



Really wide aperture version

Is depth of field a blur?

- **Depth of field is NOT a convolution of the image**
- **The circle of confusion varies with depth**
- **There are interesting occlusion effects**
- **(If you really want a convolution, there is one, but in 4D space… more about this in ten days)**

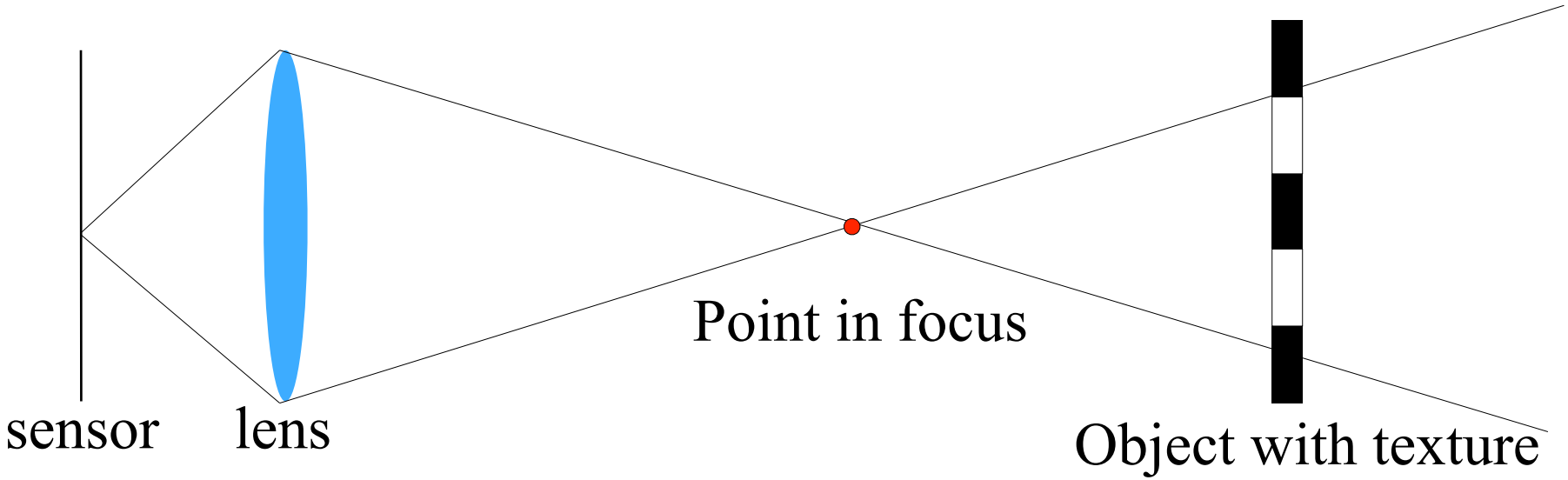


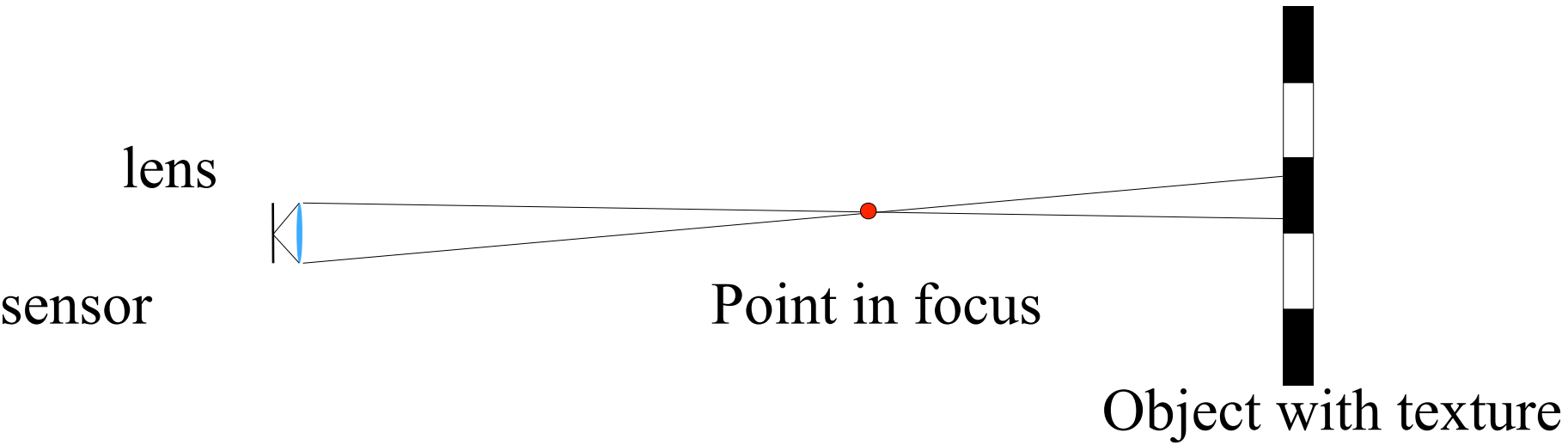
From Macro Photography

Sensor size

Depth of field

- **It's all about the size of the lens aperture**





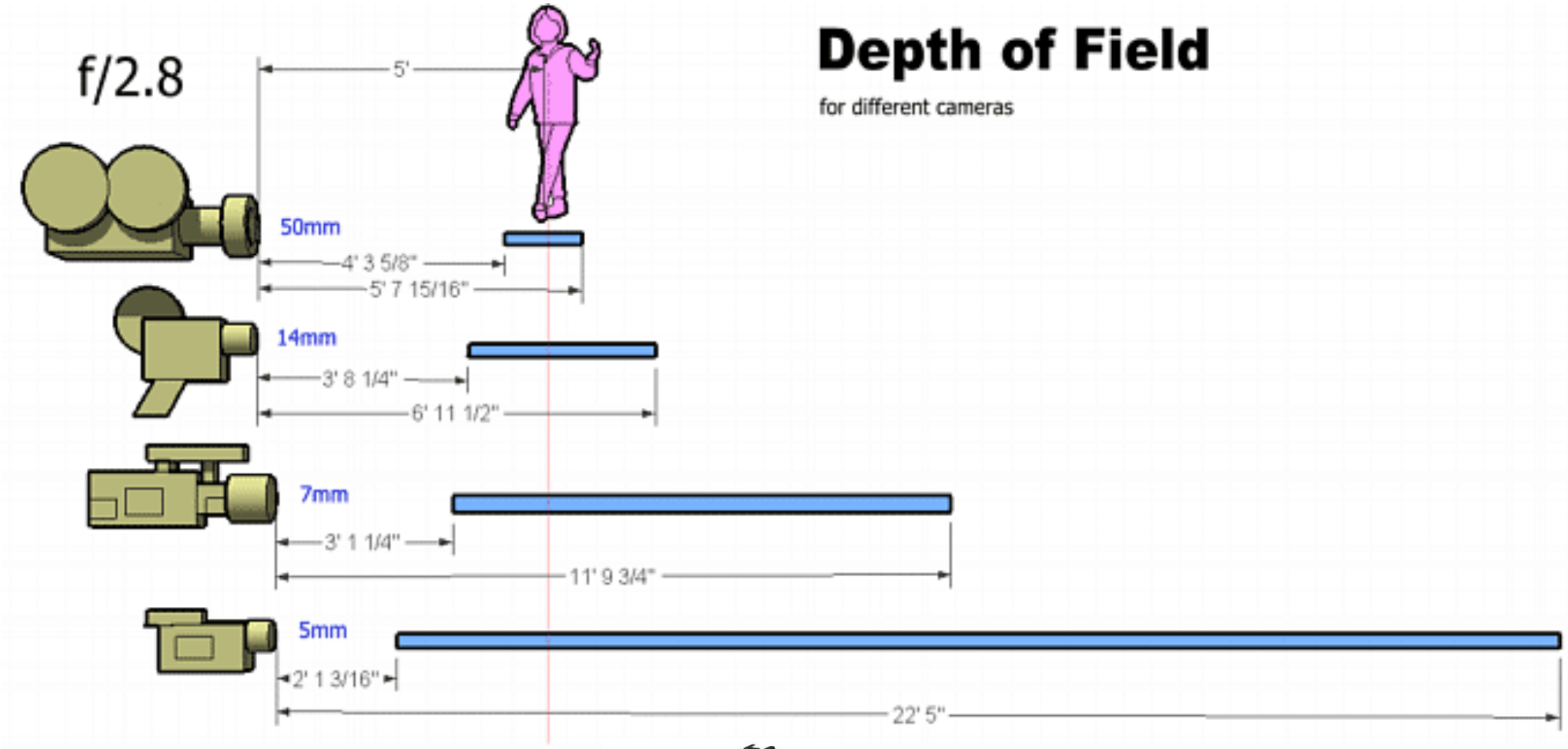
Equation

- **Smaller sensor**
  - smaller C
  - smaller f
- **But the effect of f is quadratic**
- **Bottom line: the size of the sensor linearly scales the depth of field**
  - for same field of view, focusing distance and f number (aperture).

$$d = \frac{2NCD^2}{f^2}$$

Sensor size

- http://www.mediachance.com/dvdlab/dof/index.htm

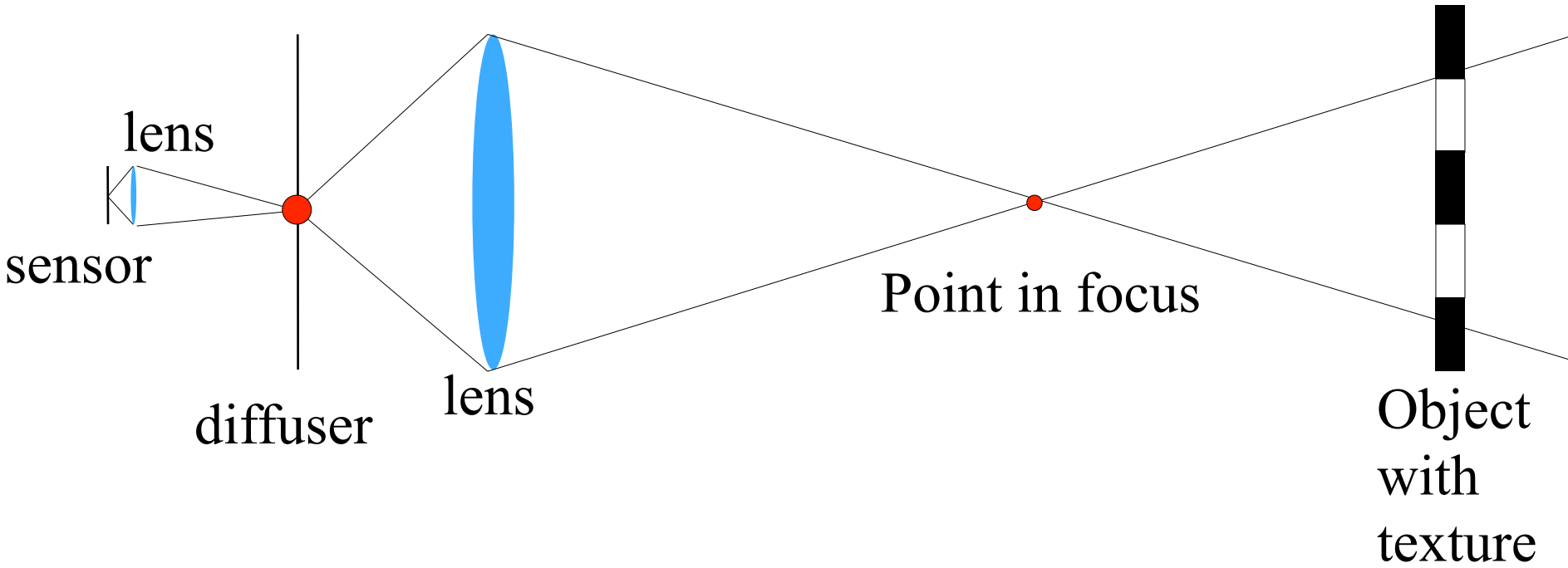






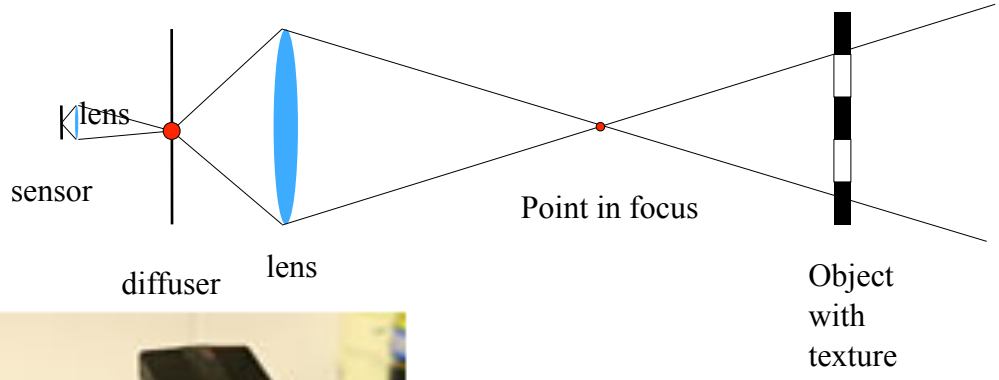
The coolest depth of field solution

- http://www.mediachance.com/dvdlab/dof/index.htm
- **Use two optical systems**



The coolest depth of field solution

- http://www.mediachance.com/dvdlab/dof/index.htm











The Frazier lens

- **The opposite: relay optics for large depth of field in macro shots.**
- **http://photo.stackexchange.com/questions/11124/how-can-a-frazier-lens-achieve-that-massive-dof**



Brenizer method

- **Simulate larger sensor using panorama stitching**
- **http://www.amazon.com/gp/blog/post/PLNK1UFLDXXBLDMN3**



Seeing through occlusion

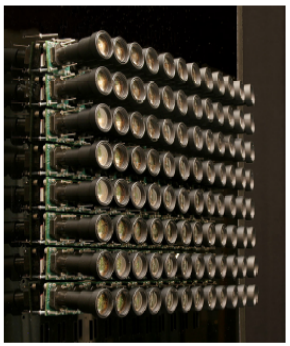
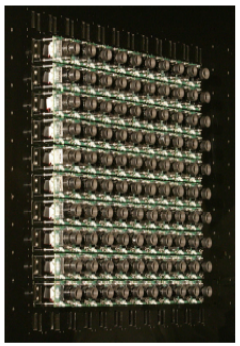
Seeing beyond occlusion

- **Photo taken through zoo bars**
- **Telephoto at full aperture**
- **The bars are so blurry that they are invisible**



Synthetic aperture

- **Stanford Camera array (Willburn et al. http://graphics.stanford.edu/papers/CameraArray/)**





(a) (b) (c)

Figure 11: Matted synthetic aperture photography. (a) A sample image from one of 90 cameras used for this experiment. (b) The synthetic aperture image focused on the plane of the people, computed by aligning and averaging images from all 90 cameras as described in the text. (c) Suppressing contributions from static pixels in each camera yields a more vivid view of the scene behind the occluder. The person and stuffed toy are more clearly visible.

Aperture

Why a bigger aperture

- **To make things blurrier**
  - Depth of field
  - outside the focal plane
- **To make things sharper**
  - Diffraction limit
  - on the focal plane

Sharpness & aperture (e.g. for the Canon 50mm f/1.4)

http://www.slrgear.com/reviews/showproduct.php/product/140/sort/2/cat/10/page/3

- **f/1.4: soft (geometrical aberrations), super shallow Dof. Lots of light!**
- **f/2.8 getting really sharp, shallow depth of field**
- **f/5.6: best sharpness**
- **f/16: diffraction kicks in, loses sharpness. But dpoth of field is big**

Depth of field

- More narrow when focusing close
- More narrow with bigger sensors
- For the same magnification, independent of focal length



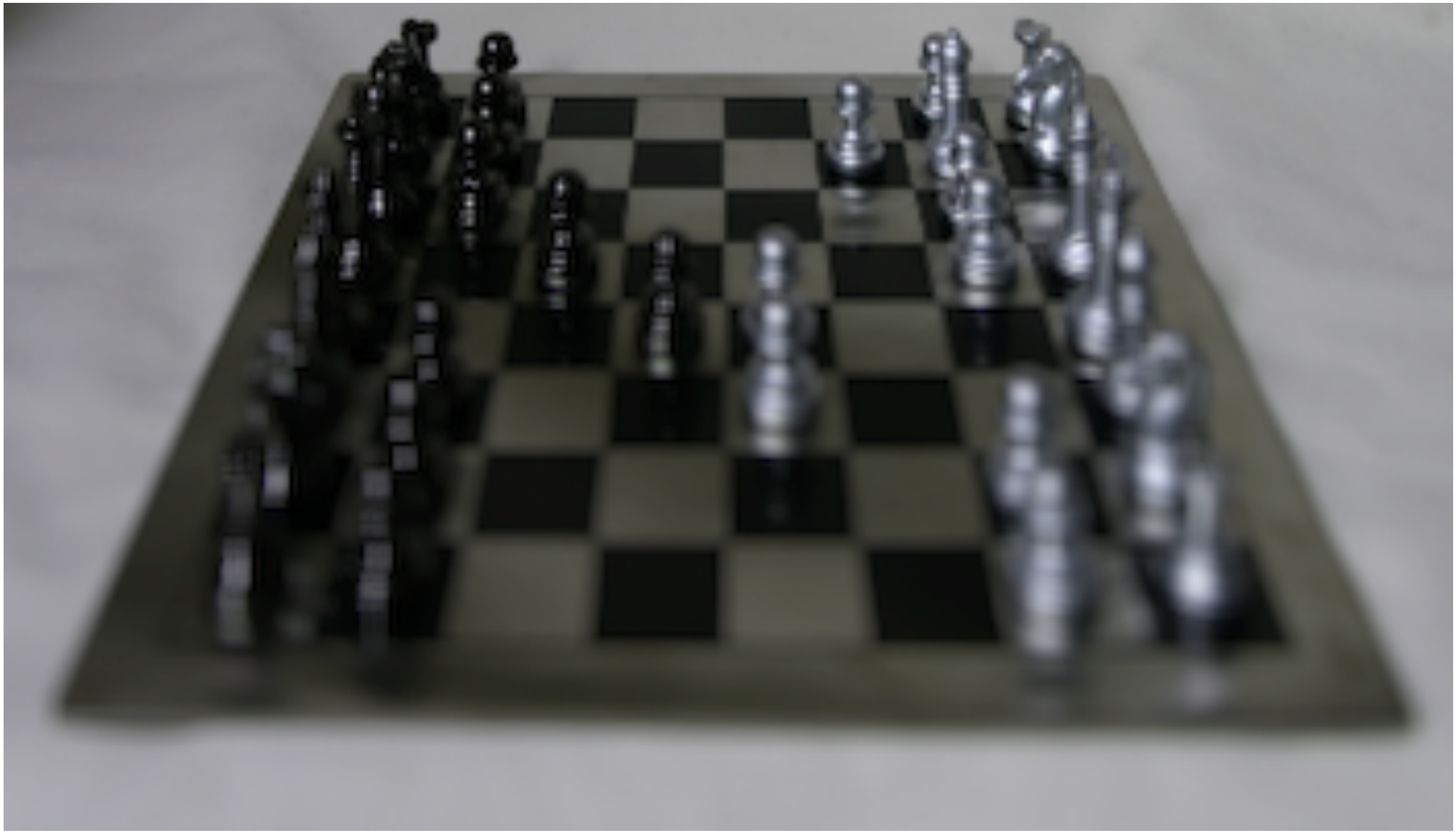




http://petapixel.com/2013/05/17/focus-stacked-macro-photos-of-bugs-by-photographer-nicolas-reusens/

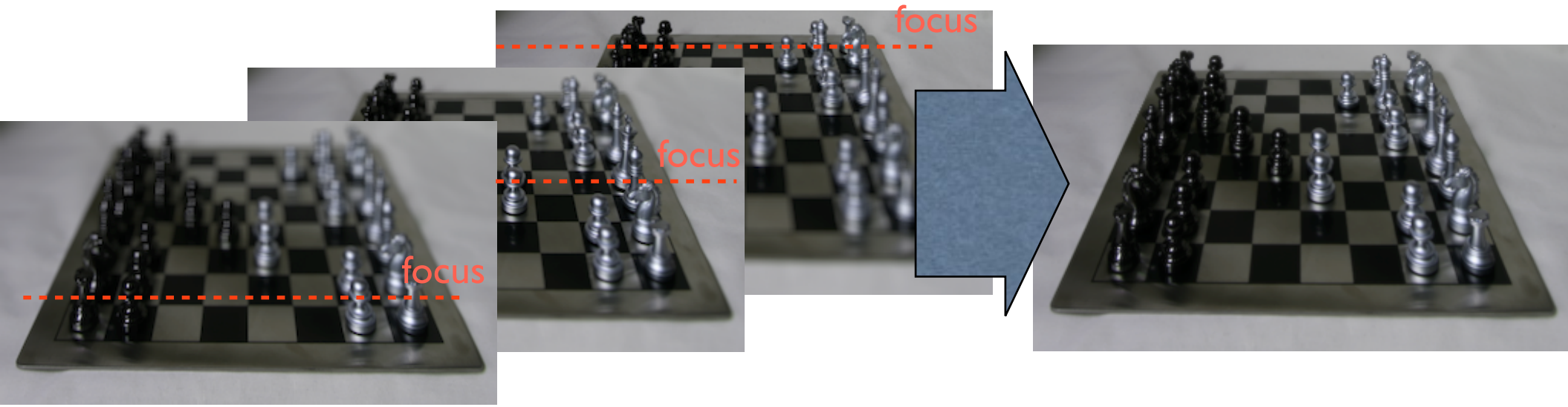
Focal stack
aka
Focus stack

Problem: limited depth of field



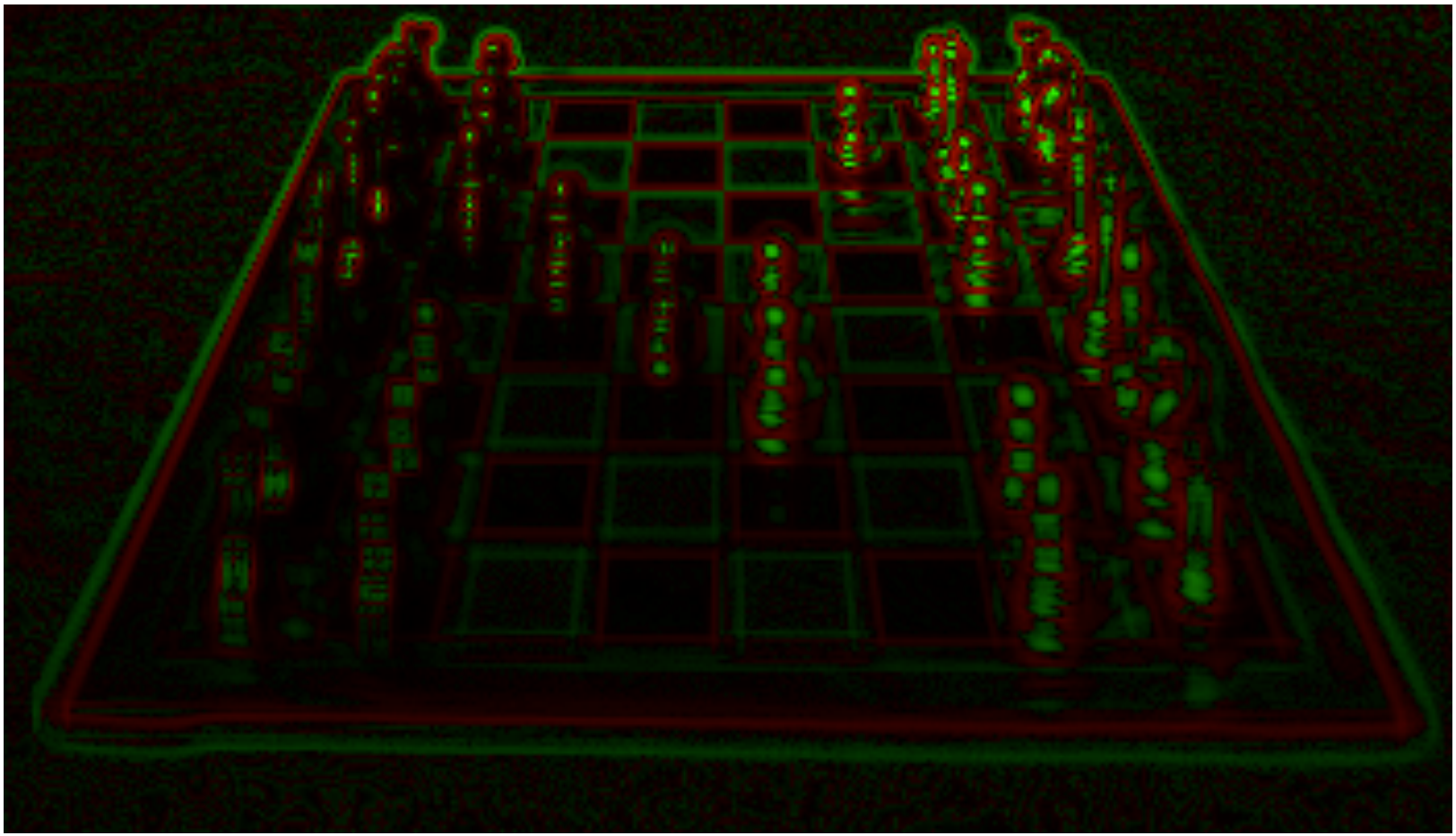
Idea

- Take images with different focusing distances
- Merge into a full-focus image
  - For each pixel, pick sharpest image
  - Similar to autofocus
- Similar to HDR, panorama
  - But along focus dimension



Evaluating sharpness

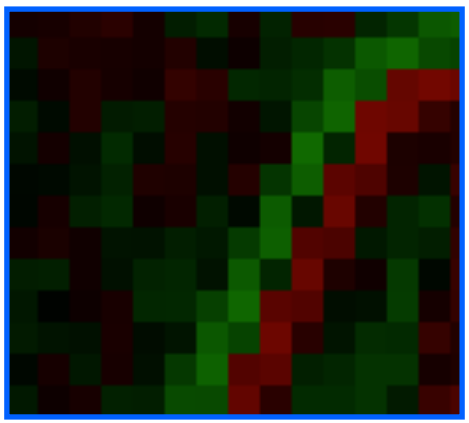
- Local amount of high-frequency content

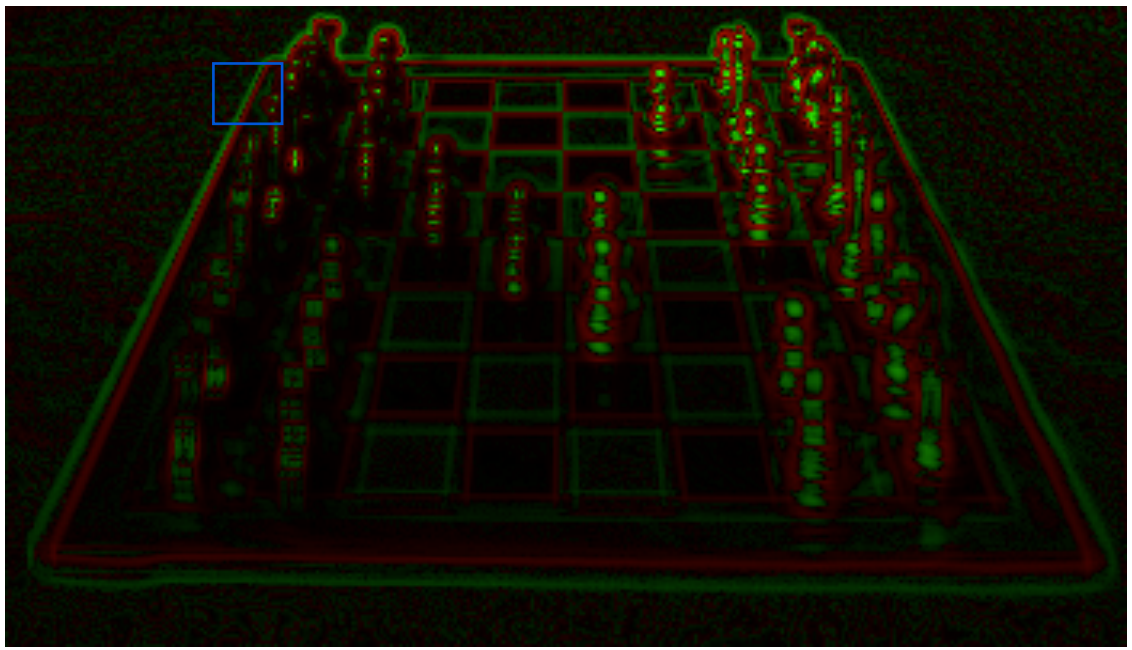


green: positive, red: negative
here image focused in the back

Need for smoothing

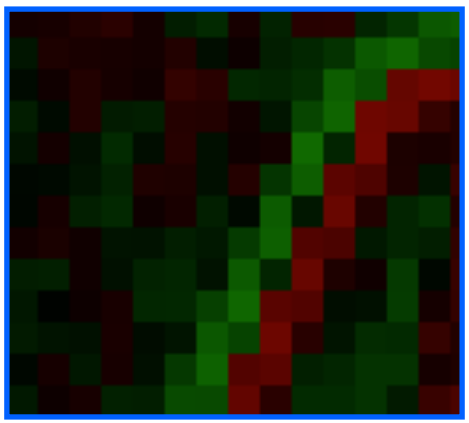
- The high frequency around an edge goes from positive to negative, through zero
- We want high “sharpness” all around the edge
- Plus we want spatial coherence in our choice of pixels

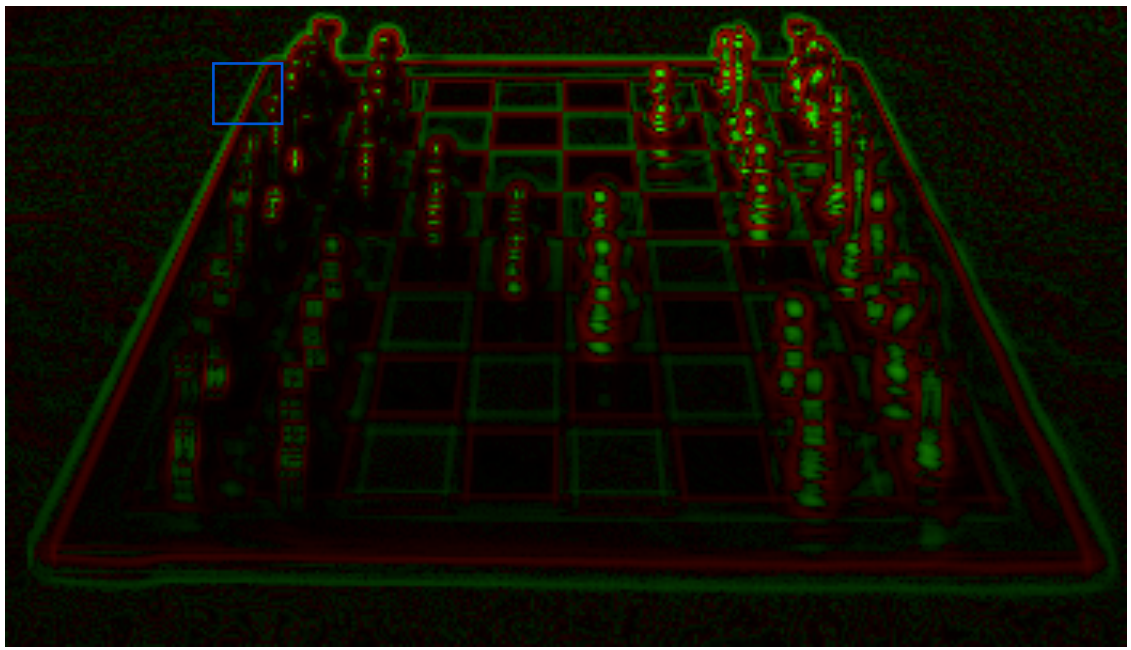




We can’t smooth directly

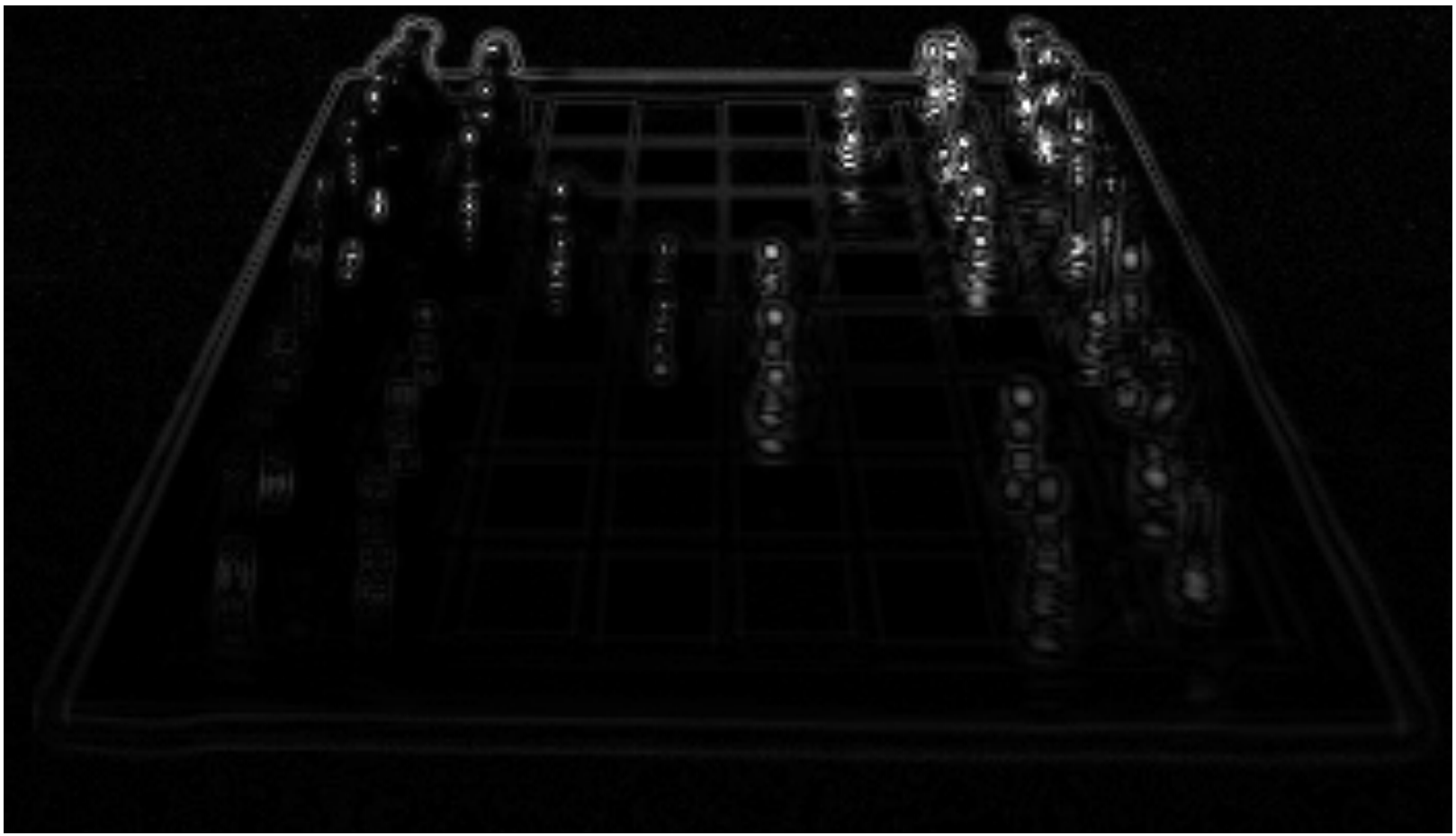
- High frequency has positive and negative values
- Local average is zero
- By construction: we removed low frequencies!





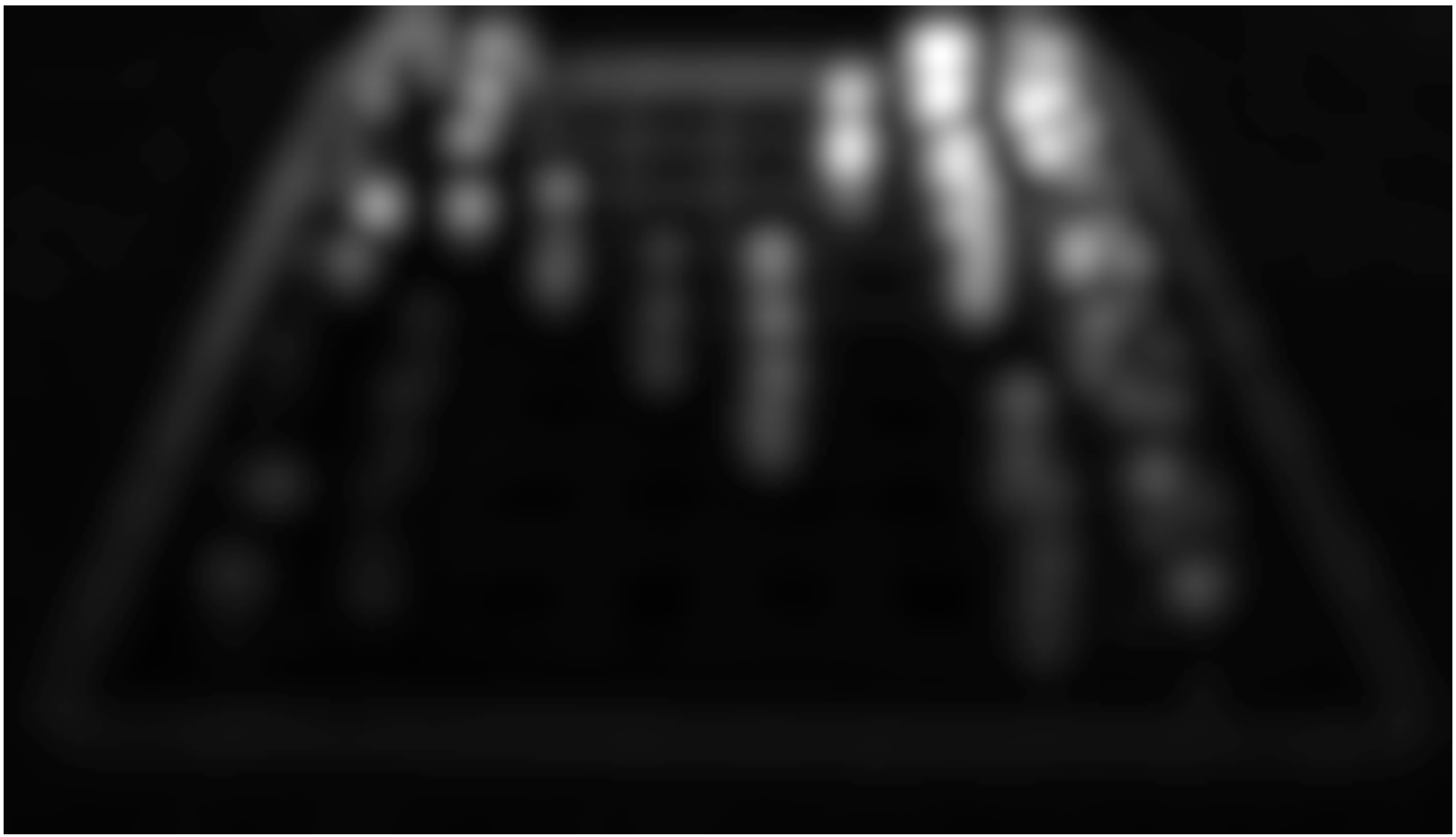
Local high frequency energy

- Take the square of the high frequencies
  - All positive



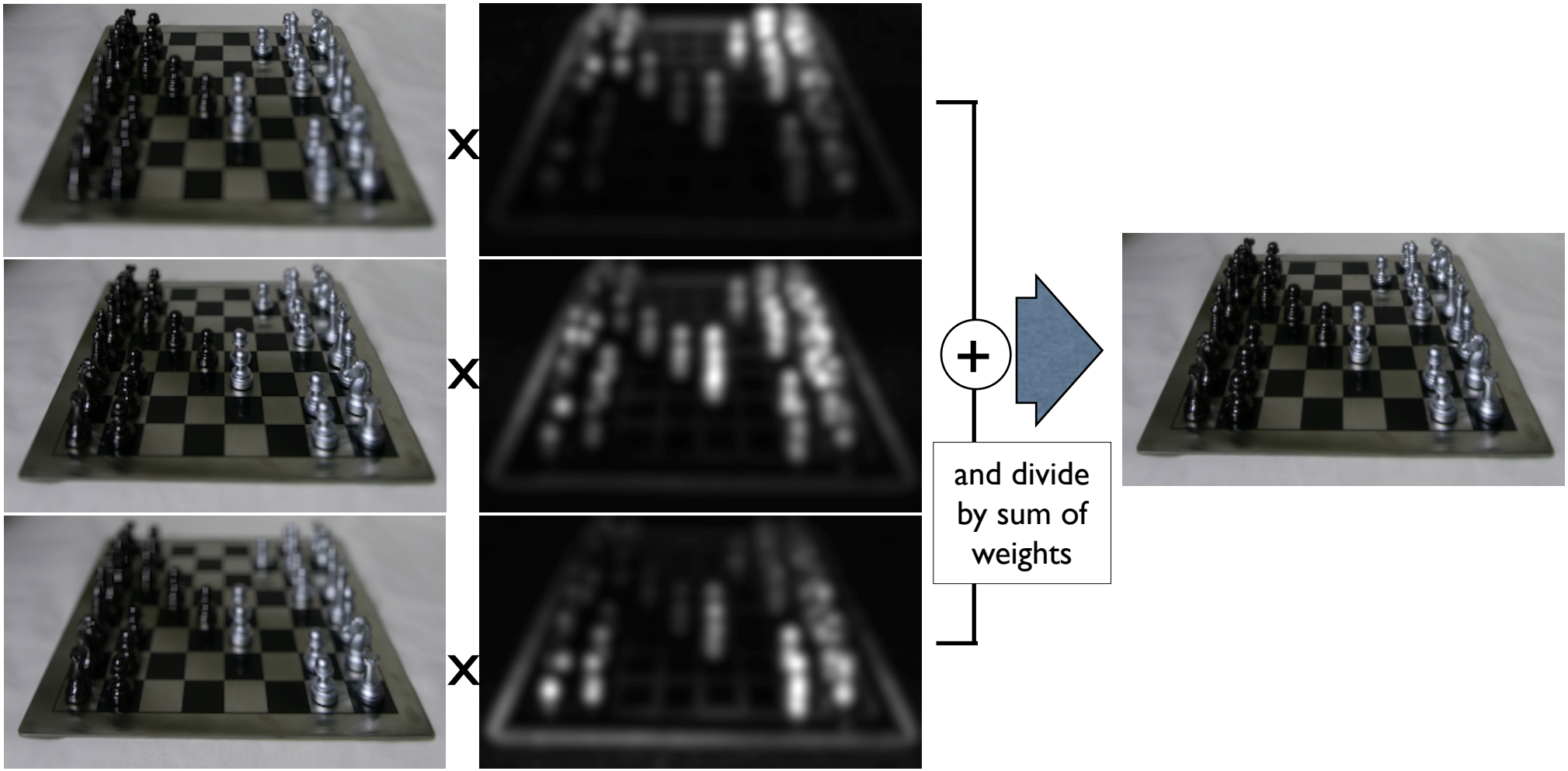
Local high frequency energy

- Take the square of the high frequencies
  - All positive
- Take local average using Gaussian filter



Focal Stack Compositing

- Weighted sum of all input images (normalize!)
- Each pixel weighted by sharpness value



Compositing (17 input images)

- Weighted sum of all input images
- Each pixel weighted by sharpness value

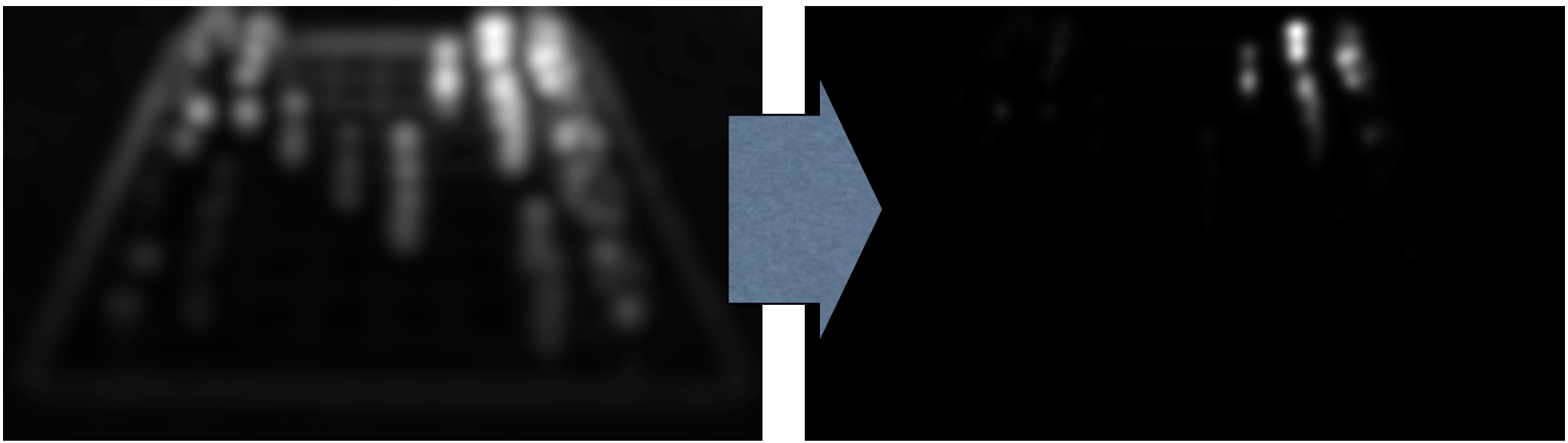


Compare to single image



Bells and whistle

- So far, simple weights
- But we want to give more weight to best image
- Potential solution: just use the max
- Simpler solution: raise the sharpness to a high exponent (e.g. 4)



With exponent 1

- (The previous version)



With exponent 4

- Subtle difference, but sharper



Visualization of image weights

- Random color for each input image



Visualization of image weights

- Random color for each input image
- With exponent =1 : blurrier



More results: input



More results: input



More results: input



More results: input



More results: input



More results: input



More results: input



More results: input



More results: input



More results: input



More results: input



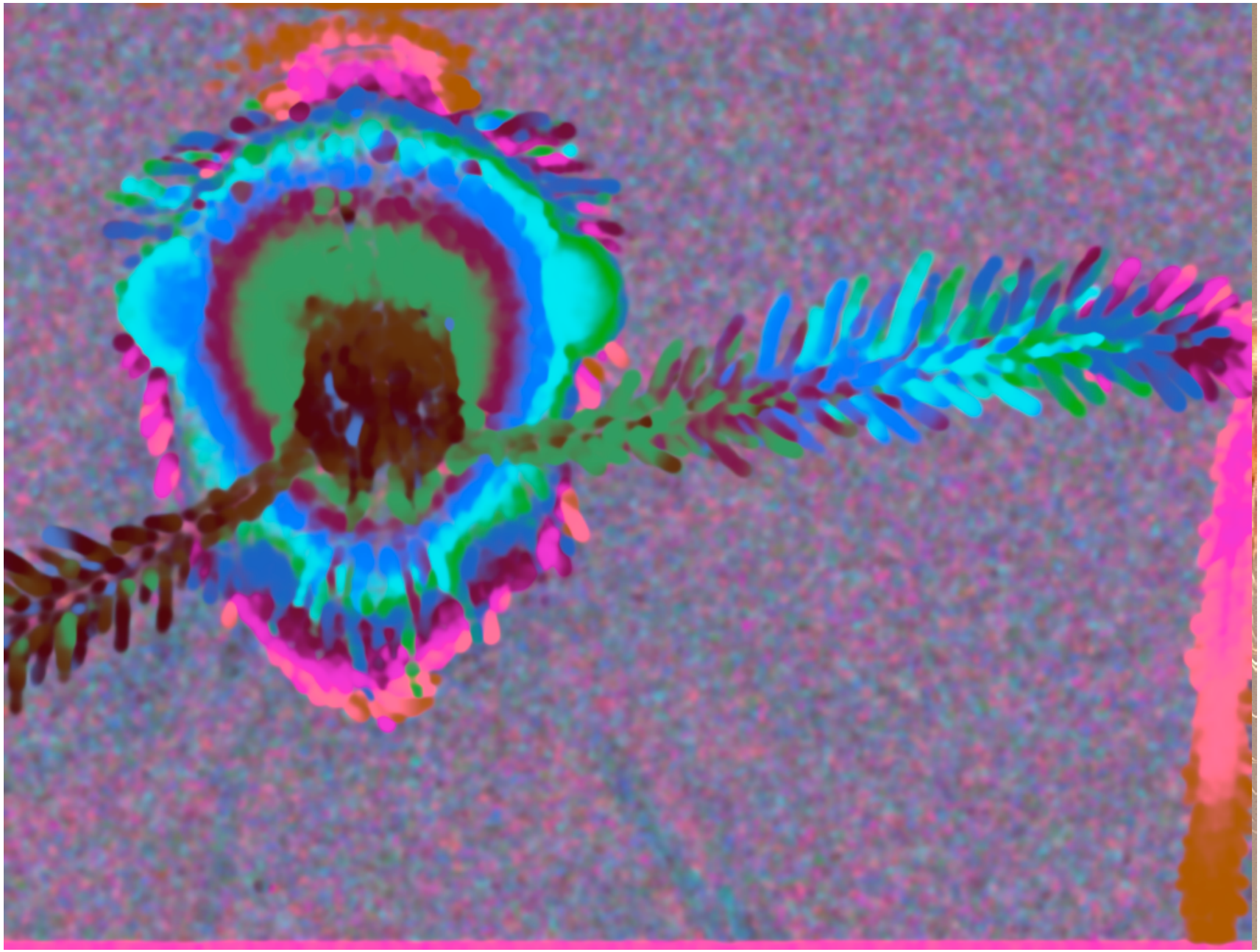
More results: input



More results

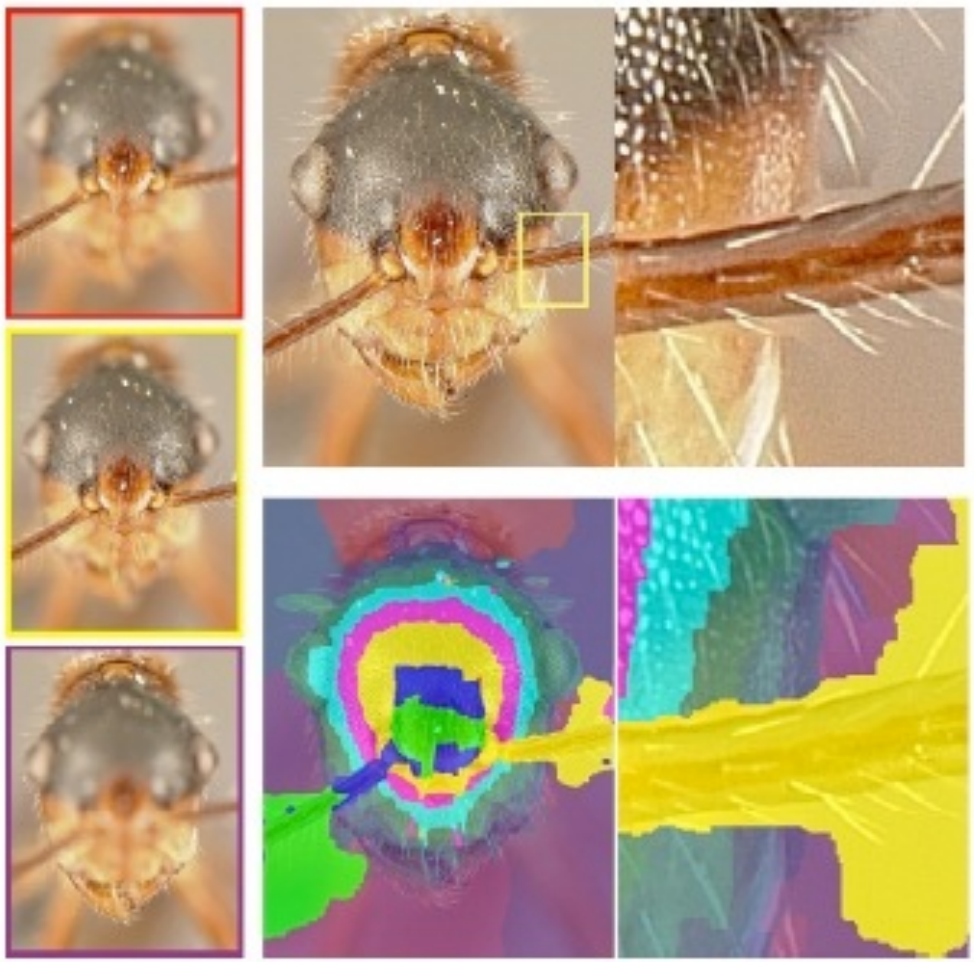


More results



More advanced

- **Choose max image for each pixel**
- **Regularize for spatial coherence**
- **Poisson (gradient) blending**



From Agarwala et al.
http://
grail.cs.washington.edu/
projects/photomontage/

Interactive Digital Photomontage



Compared to our result



Macro montage

- **55 images here**
- **Not my code**



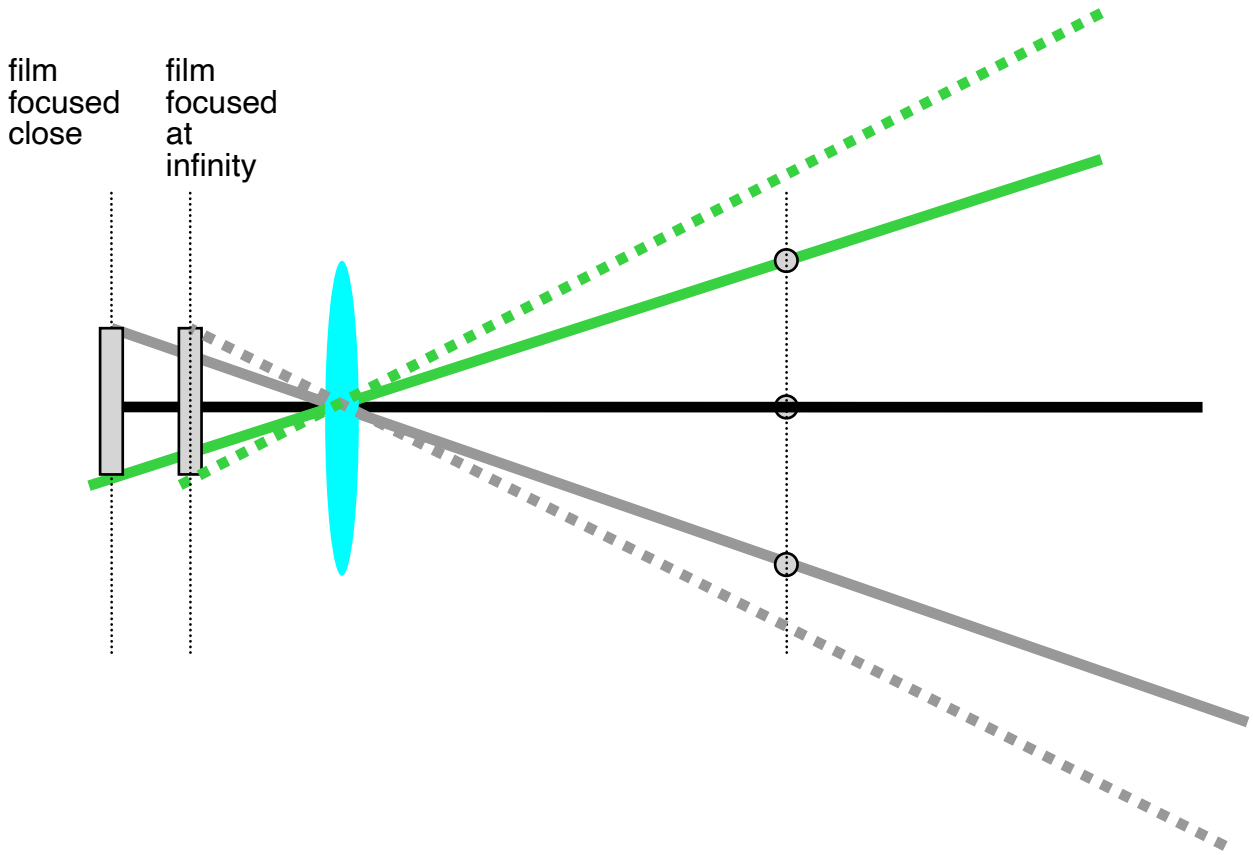
How to get the focal stack?

- http://www.cognisys-inc.com/stackshot/stackshot.php
- Although here we change the viewpoint as well



Swept under the rug

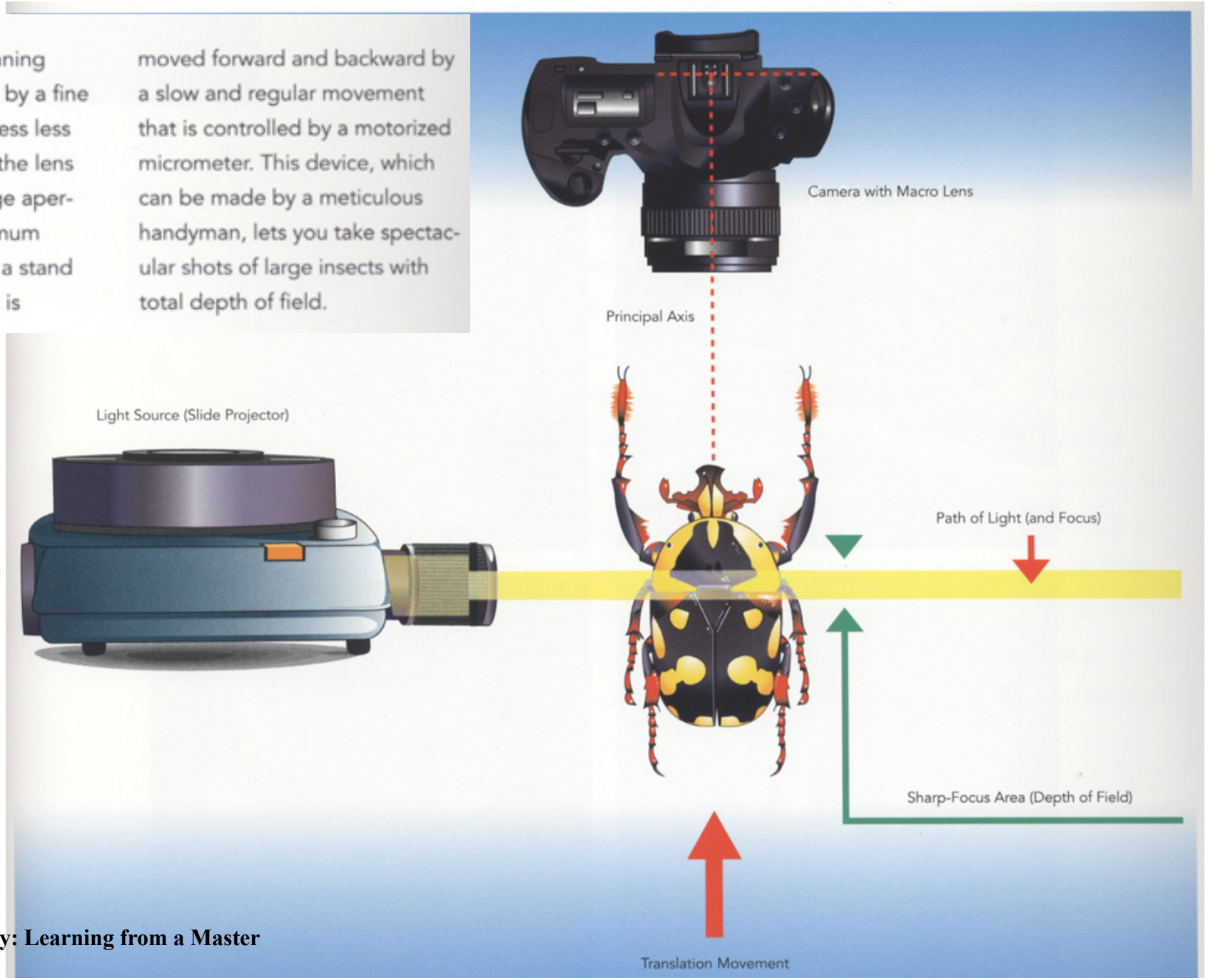
- We also need to scale images
- recall that changing the focus changes the field of view / magnification



Macro

Scanning: combination in 1 exposure

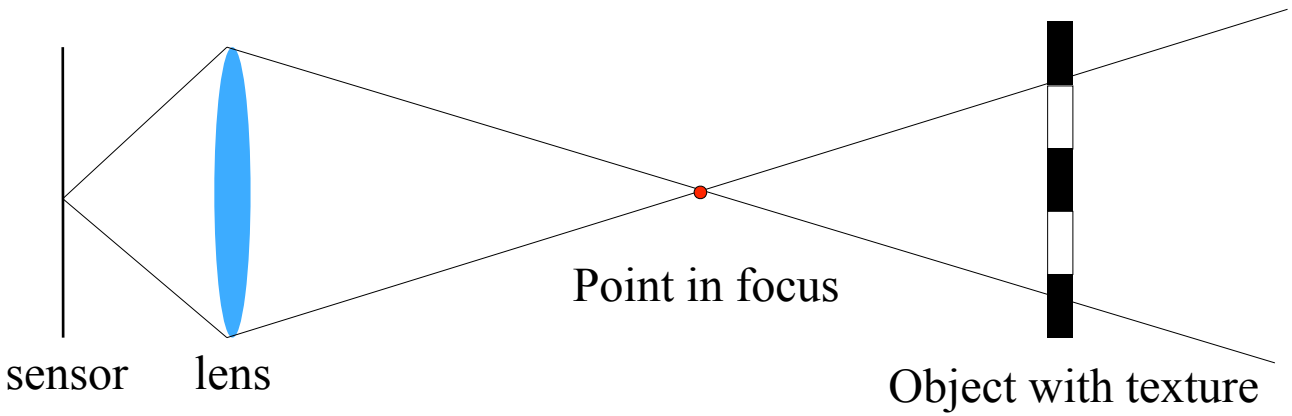
Macrophotography scanning device. The subject is lit by a fine ray of light with a thickness less than the depth of field; the lens can be used with average apertures that provide maximum sharpness. Mounted on a stand with a headless screw, it is moved forward and backward by a slow and regular movement that is controlled by a motorized micrometer. This device, which can be made by a meticulous handyman, lets you take spectacular shots of large insects with total depth of field.

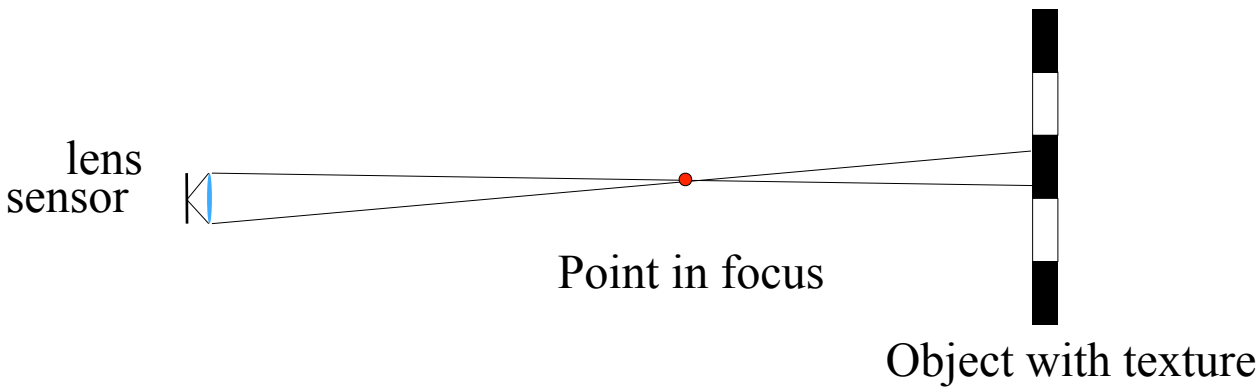


From Macro photography: Learning from a Master

Macro is easy with small sensors

- **1/ minimum focusing distance is way smaller**
- **2/ depth of field is bigger**
- **Summary: you've scaled down the camera, you can take pictures of a scaled-down world**





Well, except for diffraction
(we did not scale wavelength!)

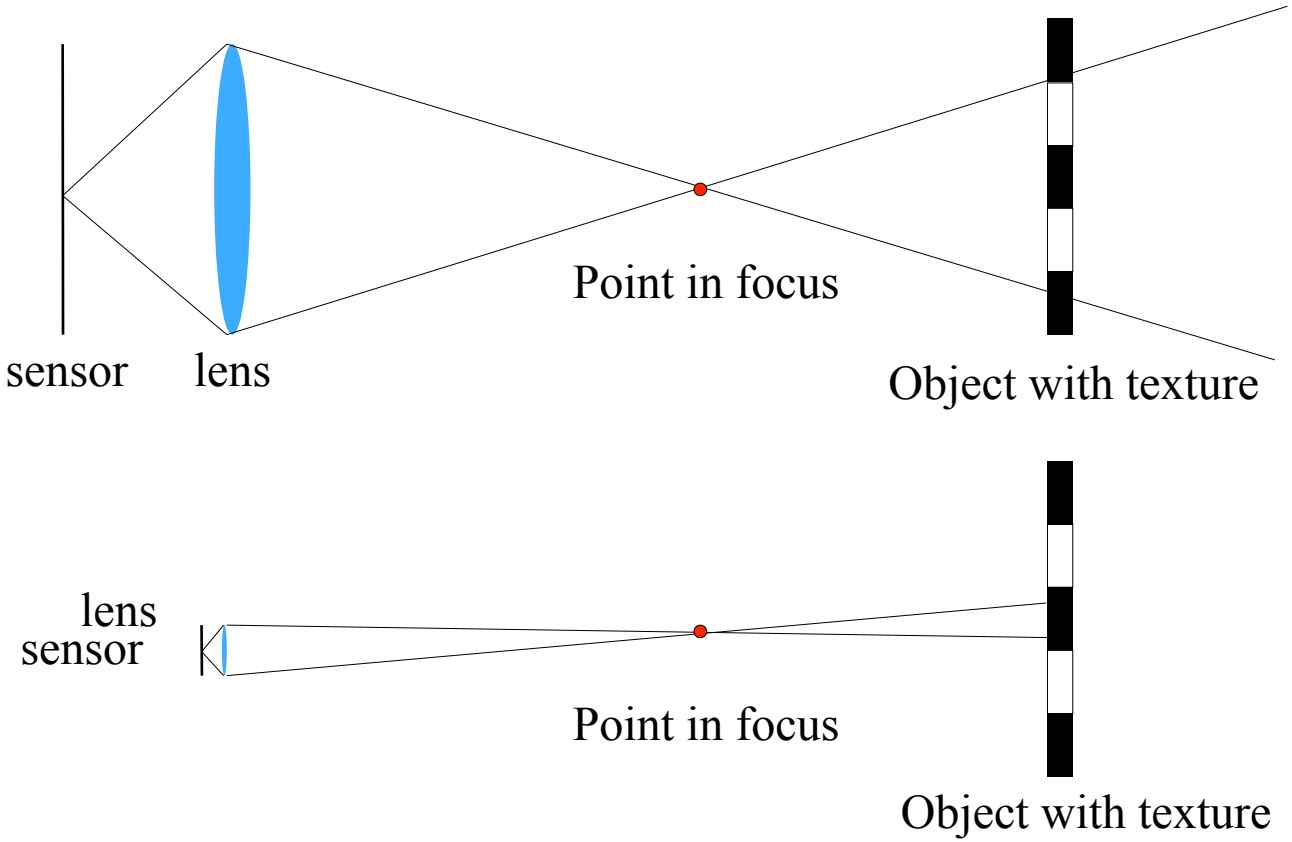
More

- http://grail.cs.washington.edu/projects/photomontage/
- http://www.heliconsoft.com/heliconfocus.html
- http://people.csail.mit.edu/hasinoff/pubs/hasinoff-timeconstrained-2009.pdf
- http://people.csail.mit.edu/hasinoff/pubs/hasinoff-timeconstrained-2009.pdf
- http://layersmagazine.com/extended-depth-of-field-with-auto-blend-layers-in-photoshop-cs4.html
- http://www1.cs.columbia.edu/CAVE/projects/flexible_dof/images/FocalStack/pool_table/
- http://en.wikipedia.org/wiki/Focus_stacking
- http://en.wikipedia.org/wiki/Microscopy#Deconvolution
- http://www.equisetites.de/palbot/tools/focus_stacking.html
- http://www.youtube.com/watch?v=fJiEw4VCcYU
- http://www.janrik.net/insects/ExtendedDOF/LepSocNewsFinal/EDOF_NewsLepSoc_2005summer.htm
- https://alliance.seas.upenn.edu/~cis581/wiki/Lectures/Pyramid.pdf
-

Fake depth of field

Challenge

- **Shallow depth of field hard with small sensors**



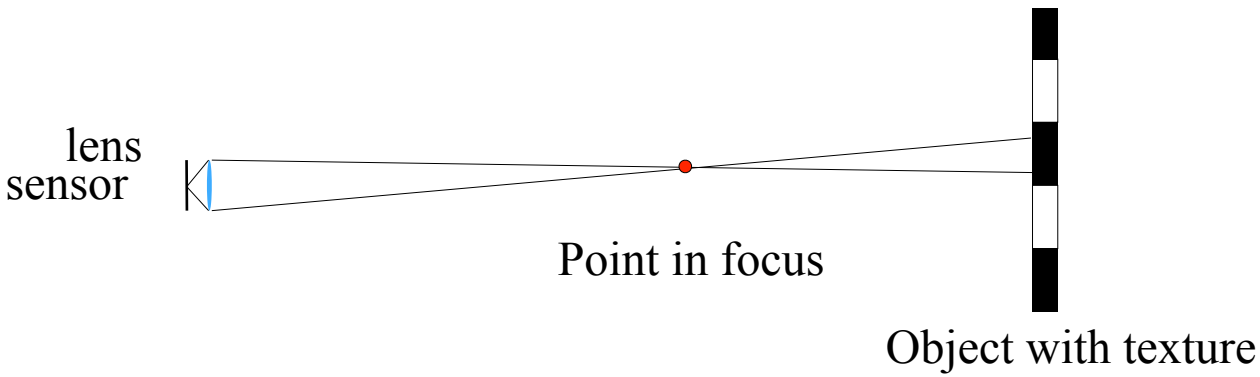
Challenge



(a) large sensor (22.2 x 14.8 mm)



(b) small sensor (7.18 x 5.32 mm)



- **https://people.csail.mit.edu/soonmin/dof/**

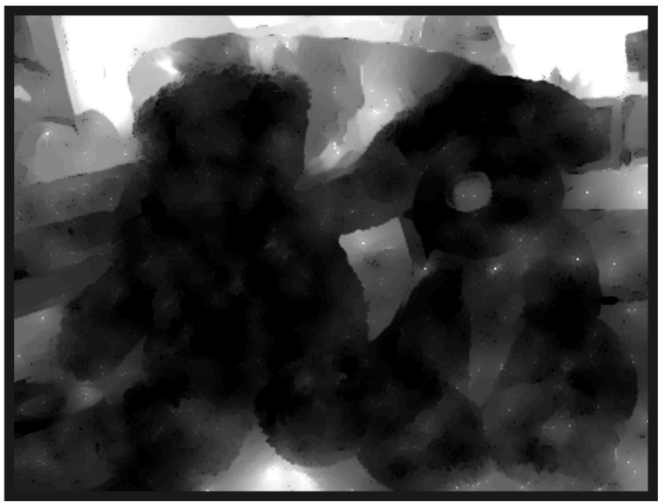
Defocus Magnification

Soonmin Bae Frédo Durand

Computer Science and Artificial Intelligence Laboratory
Massachusetts Institute of Technology



(a) input



(b) defocus map



(c) our result with magnified defocus

Figure 1: *Our technique magnifies defocus given a single image. Our defocus map characterizes blurriness at edges. This enables shallow depth of field effects by magnifying existing defocus. The input photo was taken by a Canon PowerShot A80, a point-and-shoot camera with a sensor size of 7.18 × 5.32 mm, and a 7.8 mm lens at f/2.8.*

Portrait mode

- https://research.google/blog/portrait-mode-on-the-pixel-2-and-pixel-2-xl-smartphones/
- https://arxiv.org/pdf/1806.04171





- **Machine learning-based foreground-background segmentation**
- **Use dual pixels to get a depth map (or analyze local defocus)**
- **Predict desired per-pixel blur radius**
- **Render with non-linear blur (more later)**

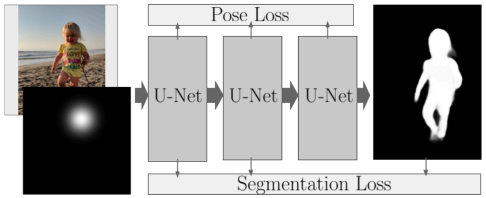
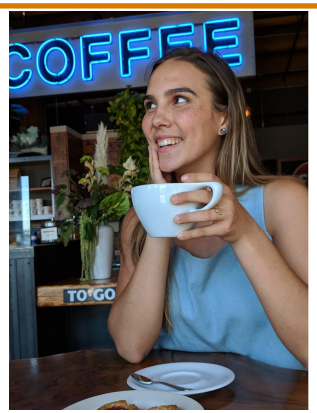
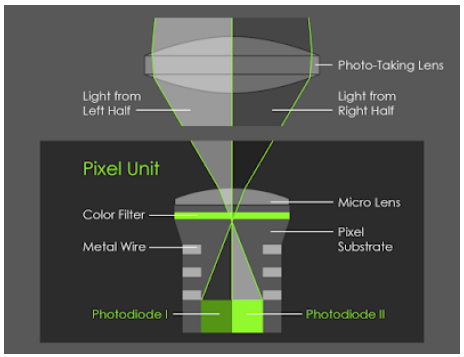


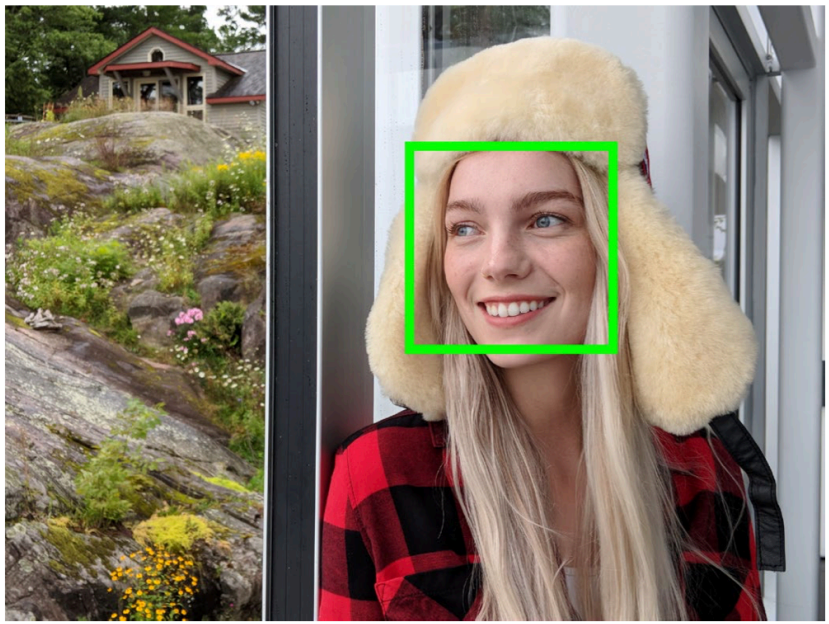
Fig. 3. **Person Segmentation Network.** RGB image (top-left) and face location (bottom-left) are the inputs to a three stage model with pose and segmentation losses after each stage.











(a) Input image with detected face



(b) Person segmentation mask



(c) Mask + disparity from DP



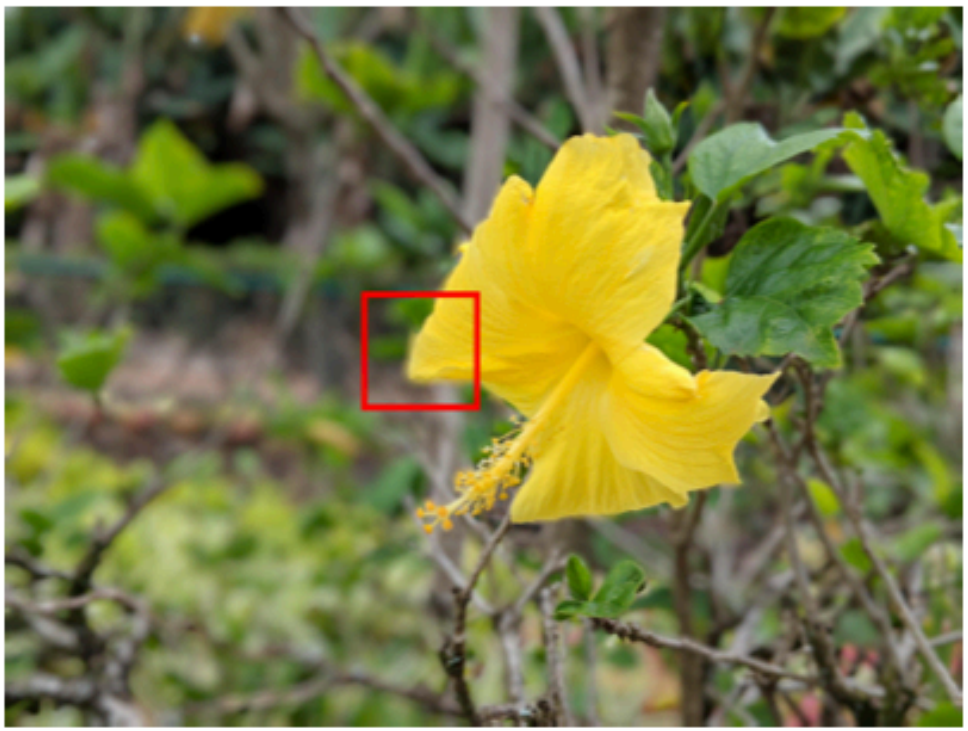
(d) Our output synthetic shallow depth-of-field image

Fig. 1. We present a system that uses a person segmentation mask (b) and a noisy depth map computed using the camera's dual-pixel (DP) auto-focus hardware (c) to produce a synthetic shallow depth-of-field image (d) with a depth-dependent blur on a mobile phone. Our system is marketed as "Portrait Mode" on several Google-branded phones.

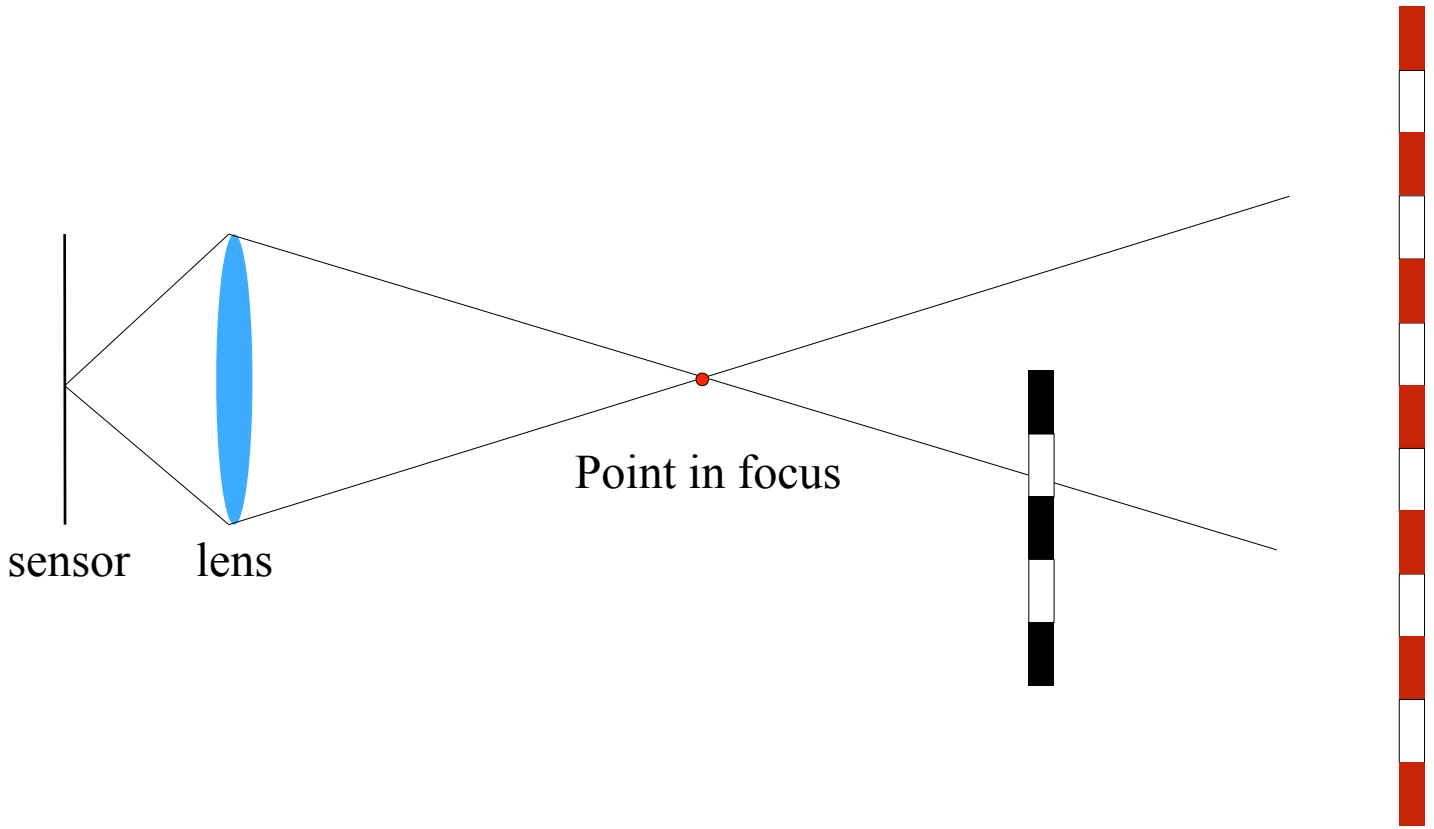
Challenge with defocus blur

- **Remember, not a convolution!**
- **Blur radius depends on input scene depth, not output pixel location**
- **Plus occlusion matters**

Naïve gather






Point in focus
sensor
lens

$$B_{scatter}(\mathbf{x}) = \sum_{\Delta \mathbf{x}} I(\mathbf{x} + \Delta \mathbf{x}) K_{\mathbf{x}+\Delta \mathbf{x}}(-\Delta \mathbf{x}).$$

Occlusion

- **Divide the image into k (=5) depth layers with opacity values**
- **Process each layer independently**
- **Composite back to front (with “over” operator)**


THC




COFFEE
TO GO


COFFEE
TO GO

Challenges

- **Masks are hard, especially around hair!**
- **Need notion of sub-pixel coverage**
-

Some more recent work

- https://arxiv.org/abs/1904.05822
- https://imaging.cs.cmu.edu/dual_pixels/

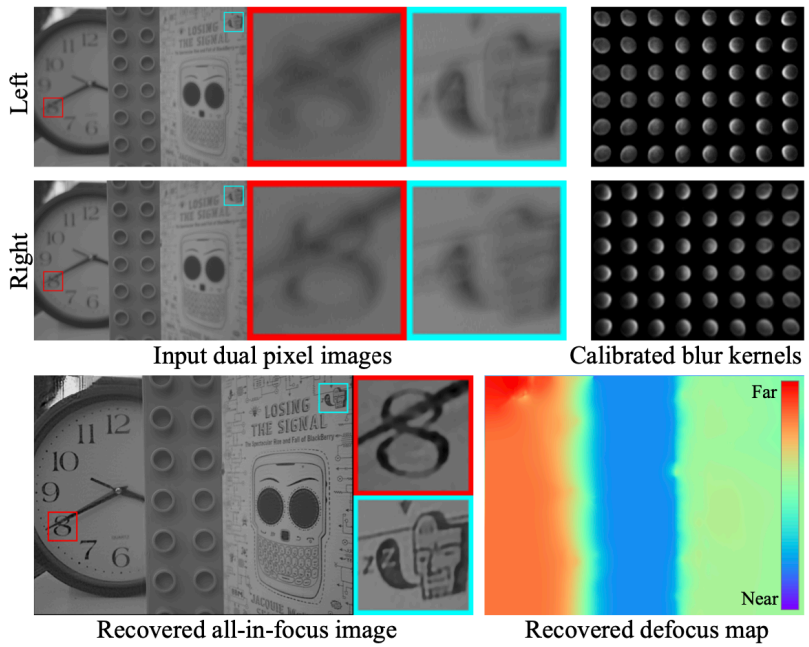


Figure 1: Given left and right dual-pixel (DP) images and corresponding spatially-varying blur kernels, our method jointly estimates an all-in-focus image and defocus map.